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Enhancing the Efficiency of Electricity Utilization Through Home Energy Management Systems within the Smart Grid Framework

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Dedicatory

I dedicate this thesis to my parents and sister, who with love, dedication, and effort, supported me unconditionally and always believed in my capabilities. Without them, nothing of this would be possible. Thank you very much.

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Resumo

O conceito por detrás das redes elétricas inteligentes está na agregação de "inteligência" à rede elétrica, quer seja através das tecnologias de sistemas de comunicação que permitam a difusão/receção de dados em tempo real, quer seja através da monitorização e controlo dos sistemas de forma autónoma. Com respeito ao avanço tecnológico, nos últimos anos tem-se verificado um aumento significativo de dispositivos e novas estratégias para a implementação em edifícios e casas inteligentes, devido sobretudo à consciencialização da sociedade relativamente às mudanças ambientais e aos elevados custos energéticos, sendo assim o tema da eficiência energética um tema cada vez mais relevante em termos das mais-valias no seio da sociedade moderna.

Nesta perspetiva, os consumidores finais são cada vez mais vistos como sendo intervenientes ativos com capacidade para gerir os seus próprios recursos energéticos, por exemplo, as unidades de microprodução descentralizada, as cargas domésticas, os veículos elétricos e a participação em eventos de resposta à demanda. A presente tese está centrada na identificação das áreas de aplicação destas tecnologias, as quais possam acarretar benefícios pela aplicabilidade das mesmas, como é caso das redes sem fios, considerando os pontos positivos e negativos de cada um dos protocolos atualmente existentes no mercado.

Posteriormente é apresentada uma avaliação da dinâmica dos preços da eletricidade e potência de pico, utilizando como exemplo um sistema de veículos elétricos e armazenamento de energia suportado por programação linear inteira-mista, no âmbito da gestão energética de uma habitação residencial. Como consequência do tema anteriormente descrito, esta tese descreverá também o desenvolvimento de um protótipo para medição de energia projetado para processar e determinar as principais grandezas elétricas e quantificar uma carga elétrica ligada a um sistema de baixa tensão em corrente alternada.

Finalmente, são apresentados dois casos de estudo relativos a um sistema de controlo preditivo e regulação térmica para aplicações domésticas com necessidade de climatização, o qual permitirá a minimização do consumo de energia considerando restrições de demanda, carga e climatização.

Palavras-Chave

Protocolos de comunicação; Eficiência energética; Veículos elétricos; Resposta à demanda; Redes elétricas inteligentes; Casa inteligente; Programação linear inteira-mista; Controlo preditivo.

Abstract

The concept behind smart grids is the aggregation of “intelligence” into the grid, whether through communication systems technologies that allow broadcast/data reception in real-time, or through monitoring and systems control in an autonomous way. With respect to the technological advancements, in recent years there has been a significant increment in devices and new strategies for the implementation of smart buildings/homes, due to the growing awareness of society in relation to environmental concerns and higher energy costs, so that energy efficiency improvements can provide real gains within modern society.

In this perspective, the end-users are seen as active players with the ability to manage their energy resources, for example, microproduction units, domestic loads, electric vehicles and their participation in demand response events. This thesis is focused on identifying application areas where such technologies could bring benefits for their applicability, such as the case of wireless networks, considering the positive and negative points of each protocol available in the market.

Moreover, this thesis provides an evaluation of dynamic prices of electricity and peak power, using as an example a system with electric vehicles and energy storage, supported by mixed-integer linear programming, within residential energy management. This thesis will also develop a power measuring prototype designed to process and determine the main electrical measurements and quantify the electrical load connected to a low voltage alternating current system.

Finally, two cases studies are proposed regarding the application of model predictive control and thermal regulation for domestic applications with cooling requirements, allowing to minimize energy consumption, considering the restrictions of demand, load and acclimatization in the system.

Keywords

Communication protocols; Energy efficiency; Electric vehicles; Demand response; Smart grids; Smart homes; Mixed-integer linear programming; Predictive control.

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Acronyms

AC	Air Conditioner
ACK	Acknowledgement
ADC	Analog-Digital Conversion
AMS	Advanced Metering System
API	Application Programming Interface
AV	Audio-Video
BAN	Body Area Network
BLE	Bluetooth Low Energy
BTU	British Thermal Units
CDH	Cognitive Digital Home
DC	Direct Current
DMA	Direct Memory Access
DR	Demand Response
EER	Energy Efficiency Ratio
EHS	European Home Systems Protocol
EIB	European Installation Bus
ESS	Energy Storage System
EV	Electric Vehicle
EWH	Electrical Water Heater
FHSS	Frequency Hopping Spread Spectrum
GFSK	Gaussian Frequency-shift Keying
GPIO	General Purpose Input/Output Pins
HAMNs	Home Area Media Networks
HAN	Home Area Network
HD	High Definition
HEM	Home Energy Management
HEMS	Home Energy Management System
HVAC	Heating, Ventilation and Air Conditioning
I2C	Inter-Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers

IETF	Internet Engineering Task Force
IIR	Infinitive Impulse Response
IP	Internet Protocol
IPSO	Internet Protocol for Smart Objects
ITU-T	International Telecommunication Union’s –Telecommunications
LAN	Local Area Network
LON	Local Operating Network
LSE	Load Serving Entity
LTI	Linear Time Invariant
M2M	Machine-to-Machine
MAC	Media Access Control
MAN	Metropolitan Area Networks
M-Bus	Meter-Bus
MCU	Microcontroller Unit
MILP	Mixed-Integer Linear Programming
MoCA	Multimedia over Coax Alliance
MPC	Model Predictive Control
MUC	Multi-Utility Controller
MV	Measured Variable
OV	Output Variable
PAN	Personal Area Network
PC	Personal Computer
PV	Photovoltaic
QoS	Quality-of-Service
QP	Quadratic Program
RAT	Radio Access Technologies
RF	Radio Frequency
RMS	Root Mean Square
SAR	Successive Approximation Register
SHEMS	Smart Home energy Management Systems
SoC	System on a Chip
SPI	Serial Peripheral Interface
TH	Thermostat

UART	Universal Asynchronous Receiver/Transmitter
UHD	Ultra-High-Definition
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
VCC	Direct Current Voltage
Wavenis-OSA	Wavenis-OSA
WH	Water Heater
WLAN	Wide Local Area Networks
WN	Wireless Network
WSN	Wireless Sensor Networks

Nomenclature

AFE	Electronic front end
CE_{ESS}	Charging efficiency of the ESS
CE_{EV}	Charging efficiency of the EV
C_{in}	Thermal capacitance of the indoor air
C_P	Specific heat of water
CR_{ESS}	Charging rate of the ESS [kW per time interval]
CR_{EV}	Charging rate of the EV [kW per time interval]
C_w	Thermal capacitance of the wall
DE_{ESS}	Discharging efficiency of the ESS
DE_{EV}	Discharging efficiency of the EV
DR_{ESS}	Discharging rate of the ESS [kW per time interval]
DR_{EV}	Discharging rate of the EV [kW per time interval]
ε_2	Priority parameter of ESS
ε_3	Priority parameter of EV
f_s	Sampling Frequency
G_{ADC}	ADC gain
IIR	Infinite impulse response
I_{Load}	Sensed current
K_{CS}	The signal conditioning circuit gain
K_{CT}	Traducer gain
M	ADC resolution
m	Mass of water
N_1	Maximum power that can be drawn from the grid [kW]
N_2	Maximum power that can be sold back to the grid [kW]
N_{code}	ADC code
η	Efficiency
$P_t^{ESS,ch}$	ESS charging power [kW]
$P_t^{ESS,dis}$	ESS discharging power [kW]
$P_t^{ESS,sold}$	Power injected to grid from the ESS [kW]
$P_t^{ESS,used}$	Power used to satisfy household load from the ESS [kW]

$P_t^{EV,ch}$	EV charging power [kW]
$P_t^{EV,dis}$	EV discharging power [kW]
$P_t^{EV,sold}$	Power injected to grid from the EV [kW]
$P_t^{EV,used}$	Power used to satisfy household load from the EV [kW]
P_t^{grid}	Power supplied by the grid [kW]
$P_t^{PV,sold}$	Power injected to grid from the PV [kW]
P_t^{other}	Household power demand [kW]
$P_t^{PV,pro}$	Power produced by the PV [kW]
$P_t^{PV,used}$	Power used to satisfy household load from the PV [kW]
P_t^{sold}	Total power injected to the grid [kW]
P	Factor is used to determine the cut-off frequency of the IIR filter
Q_{ac_ht}	Thermal source
Q_{eg}	Electric power
Q_{in}	Heat to be extracted
Q	Total reactive power
R_c	Thermal resistance of windows
R_w	Thermal resistance of walls
SNR	Signal-to-noise ratio
$SOE^{ESS,ini}$	Initial state-of-energy of the ESS [kWh]
$SOE^{ESS,max}$	Maximum allowed state-of-energy of the ESS [kWh]
$SOE^{ESS,min}$	Minimum allowed state-of-energy of the ESS [kWh]
$SOE^{EV,ini}$	Initial state-of-energy of the EV [kWh]
$SOE^{EV,max}$	Maximum allowed state-of-energy of the EV [kWh]
$SOE^{EV,min}$	Minimum allowed state-of-energy of the EV [kWh]
SOE_t^{ESS}	State-of-energy of the ESS [kWh]
SOE_t^{EV}	State-of-energy of the EV [kWh]
S_p	Set-point
S	Binary variable
T^a	Arrival time of EV to household
T_{amb}	Ambient Temperature
T^d	Departure time of EV from household
$T^{f,c}$	Period at which EV should be fully charged
$T^{f,d}$	Period at which EV should be fully discharged, if applicable

T_{in}	Temperature in the room
T_{inlet}	Inlet water temperature
T_w	Temperature of the wall
T	Acquisition time Window
t	Period of the day index in time units [h or min]
UA	Characteristic of fiber glass
$U_{pk-to-pk}$	Tension peak-to-peak
u_t^{ESS}	Binary variable: 1 if ESS is charging during period t, 0 else
u_t^{EV}	Binary variable: 1 if EV is charging during period t, 0 else
u_t^{grid}	Binary variable: 1 if grid is supplying power during period t, 0 else
V_{IS}	Output Voltage
V_k	Voltage sample
V_{OC}	Offset voltage related to the transducer zero current
ΔT	Number of time intervals in one hour
ε_1	Priority parameter of PV
λ_t^{buy}	Price of energy bought from the grid [cents/kWh]
λ_t^{sell}	Price of energy sold back to the grid [cents/kWh]

Chapter 1

Introduction

This Introduction has been divided in multiple subjects in order to better understand and differentiate them. The first part, framework, is to introduce the reader in the situation and give a general idea on energy consumption, resource scarcity over the years and the high CO_2 production that is associated to climate change. Also, the motivations that support the proposed work are described, as well as an overview about the thesis organization and the notation used.

1.1. Framework

The access to energy is fundamental to the development of societies. However, most of the energy used in the world comes from fossil fuels like coal, gas or oil, whose reservations have been decreasing. In addition, the intensive use of fossil fuels increases carbon dioxide concentration in the atmosphere, contributing to global warming. The use of energy inefficiently implies unnecessary consumption of fossil fuels having an extremely negative impact on the environment [1]. In recent decades, industrialized countries have adopted economic development policies to increase the well-being of the population, based on large energy consumption and resulting environmental impact and scarcity of world energy resources.

As shown in Figure 1.1, in 2014, the world energy consumption reached approximately the value of 13 million tonnes oil equivalent [2]. With a global energy as dependent on fossil fuels, there is a large issue of greenhouse gases with direct impact on increasing the temperature of the planet and enhancing climate change. These changes are reflected in the increase in the average level of the oceans by liquefying the poles, desertification and the increased frequency of natural disasters [3]. According to the Intergovernmental Panel on Climate Change (IPCC), a United Nations agency, global temperature could increase (in an extreme scenario) up to 6.4ºC by the end of this century.

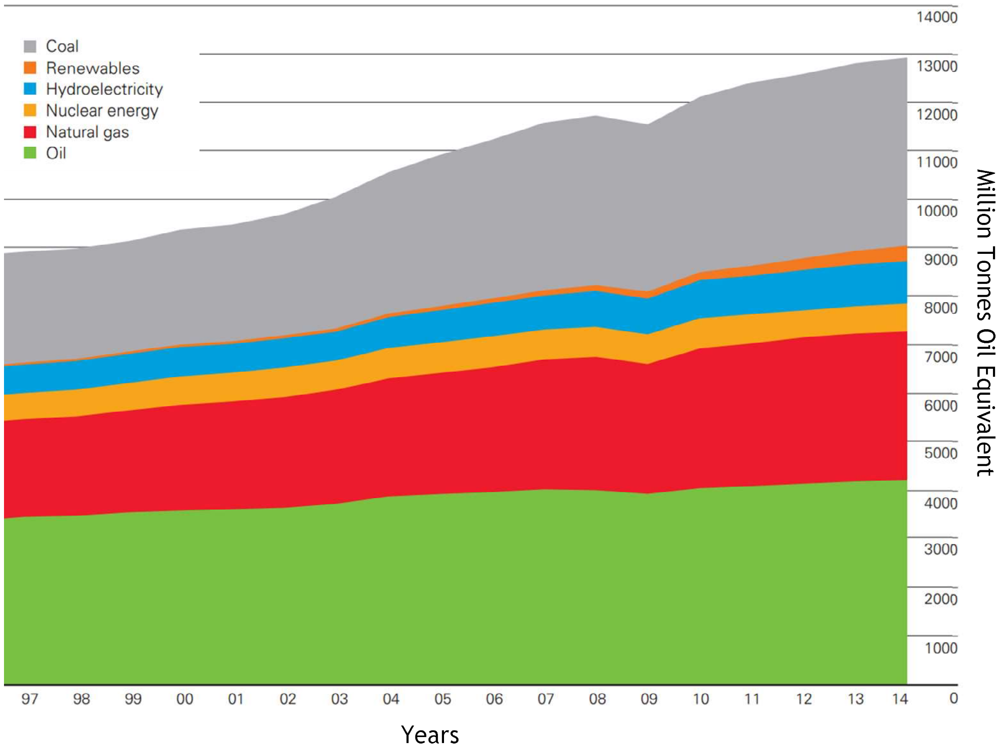


Figure 1.1. Evolution and distribution of world energy consumption from 1997-2014 [2].

To avoid this, a comprehensive policy should aim to keep this increase in less than 2ºC, or even 1.5ºC, in relation to the temperature registered before the Industrial Revolution in the 18th century [4]. With a warming above 2ºC, the change of the climate system and damage to ecosystems and human populations will be much more drastic than those already felt today: melting glaciers and the consequent rise in sea level; melting permafrost (frozen soil of the Arctic region) and the release of methane stored in these areas today, changing the chemical composition of the oceans, destroying coral reefs, extreme weather events such as storms, floods, heat waves and droughts, more frequent and more intense [5].

Moreover, the greenhouse effect is the process by which the atmosphere traps some of the energy radiated by the sun and turns it into heat, warming the Earth and preventing a very large fluctuation of temperatures on the planet. As shown in Figure 1.2, in 2013 the electricity sector was the largest source of U.S. greenhouse gas emissions, accounting for about 31% of the U.S. total. Greenhouse gas emissions from electricity have increased by about 11% since 1990 as electricity demand has grown and fossil fuels have remained the dominant source for generation [2], [6].

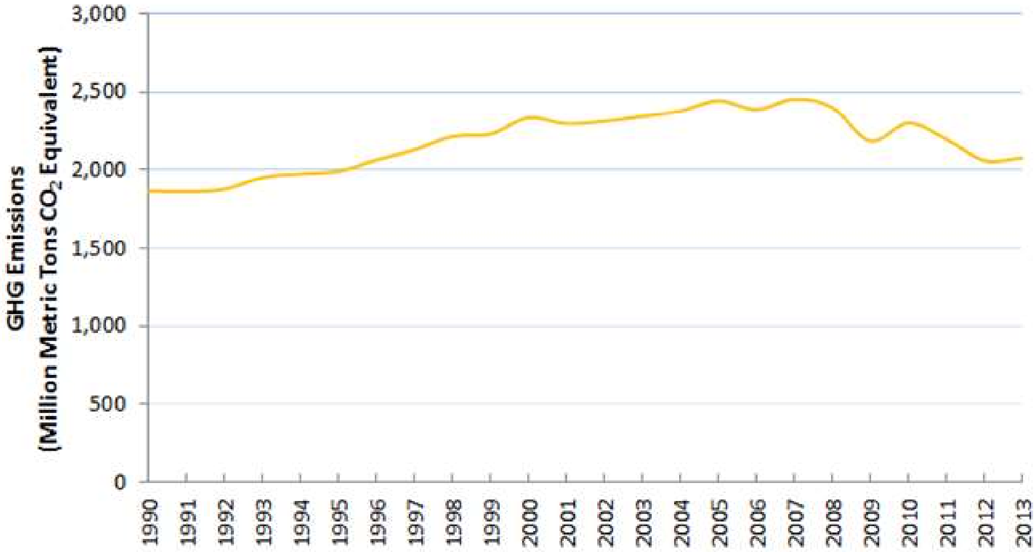


Figure 1.2. Greenhouse Gas Emission from electricity: 1990-2012 [3].

Hence, climate changes have taken to the emergence of a concept that has become essential today, to energy efficiency. Energy efficiency can be defined as the optimization or rationalization that can be applied to energy consumption. This concept is based on the implementation of strategies and measures to combat energy waste throughout the transformation process, ranging from the purchase of energy resources to energy use, monitoring their entire production and distribution process. Given the expiration of the Kyoto Protocol in 2012, talks were already under way for a new international agreement, which appears to be difficult to achieve, given the modest agreements reached in Copenhagen in 2009 and Cancun in 2010 [7]. The world energy matrix remains highly dependent on the burning of fossil fuels and therefore the increase in greenhouse gas emissions has continued frustrating the aims of this Protocol.

Consequently, reducing emissions of greenhouse gases implies a lower power consumption and greater use of clean energy. The policy imposes the following targets [8], [9]: reduce 20% of energy consumption through higher efficiency; reduce anthropogenic greenhouse emissions by 20%; 20% of the energy consumed should come from renewable energy sources. Figure 1.3 shows the total anthropogenic greenhouse gas emissions ($GtCO_{2eq}$) by economic sectors, in 2010. The inner circle shows direct greenhouse gas emissions shares (in % of total emissions) of five economic sectors in 2010.

This figure shows how indirect CO_2 emission shares (in % of total emissions) from electricity and heat production are attributed to sectors of final energy use. "Other Energy" refers to all greenhouse gas emissions sources in the energy sector [4]. The emissions data from Agriculture, Forestry and Other Land Use (AFOLU) includes land-based CO_2 emissions from forest fires, peat fires and peat decay that approximate to net CO_2 flux from the Forestry and Other Land Use (FOLU) sub-sector [4].

In the last decades, a deep change in energy consumption habits of Portuguese families has occurred. With the increasing economic power and the improvement of living conditions, people sought to have better comfort conditions, leading to an increase of energy consumption in buildings. In Portugal, buildings are responsible for about 26% of final energy consumption in the country [10]. The electric energy consumption in domestic sectors and services sectors account for 58% of this consumption, so it is natural that there should be an effort to improve energy efficiency of buildings [11].

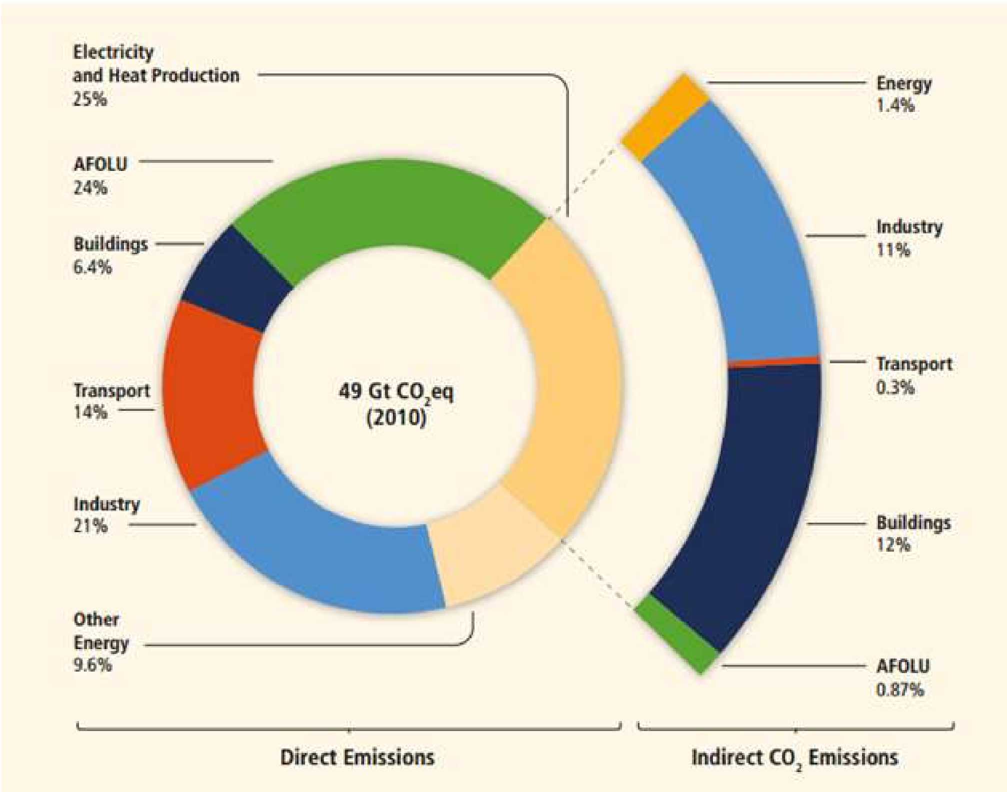


Figure 1.3. Total Greenhouse Gas Emissions by Economic Sectors [4].

The average annual increase in electricity consumption has been more than 6% in the last 20 years [12]. The rational use of energy has become one of the important ways to reduce the rise in energy consumption in the building sector.

These actions can be grouped into two major groups: the technological policy and the energy policy. The first group aims to increase energy efficiency by acting at the level of equipment and control systems, improved energy efficiency and the behavior of users. The second group aims to eliminate any barriers, such as the lack of regulation in a given area, or to make adjustments to the consumption of a particular energy source, through an energy pricing policy or subsidy/tax benefit in using a given technology [13].

The continued growth of energy consumption in the residential sector is linked to the growing electricity consumption in homes, caused by the introduction of new equipment aimed at providing increased living standards of the population and the thermal comfort of the occupants.

However, the introduction of new equipment has increased the energy bill and external dependence. This growing trend of electricity consumption will tend to continue to increase due to the growing number of electrical equipment currently used in homes [14].

In the last decade, there has been a major technological breakthrough in the areas of sensors, integrated circuits and wireless communications, which lead to the creation of wireless sensor networks. This type of network may be used for monitoring, tracking, processing and coordination in different contexts. For example, it can interconnect sensors to the monitoring and domestic load control and demand control.

The interconnection of sensors through wireless networks aims at collecting and processing information to make an even smarter and sustainable system. In contrast, the world electricity use is expected to increase by 90% by 2050, with developing countries aiming to improve living standards even further.

Other contributions include expanding the use of the Internet, wireless communications and other information technologies. Public utilities and other energy producers can choose from a variety of fossil fuels and other energy sources to produce electricity.

By 2050, it is expected that public policies that establish tighter standards and/or higher costs for emissions of CO_2 will accelerate the disappearance of coal and, at the same time, promote the use of renewable energy. Therefore, the energy revolution scenario takes into account not only the way we produce but also the way we consume electricity. By 2050, it is expected that 26% of energy demand can be reduced with the implementation of stringent measures. It is cheaper and simpler to invest in energy efficiency to generate more energy, with many measures that can be taken individually [15].

By tracing this scenario, we begin to better understand the need to save energy, which is directly related to sustainability. So, the residence sector is already showing clear signs of rational use of energy, gas and also control of water consumption. The amount of construction of the so-called “green buildings” is being increased, as well as the pursuit of a “green seal” for buildings already built [16].

In the next decades, according to the reassessment of technological change, the classification of equipment must keep in perspective the reduction of consumption. The energy available when a device is in standby is wasted energy, such as it occurs in television, computers and printers; this energy consumption accounts for 30% to 40% of the total [17].

In developed countries, energy consumption in appliances in standby varies between 20W and 90W for housing, ranging from 4% to 10% of the total electricity used. In emerging economies, the number of household appliances is on the rise. In China, for example, the energy used by devices in standby was almost zero in the 1980s, but in 2000 it became responsible for 50 to 200 kWh per year per residence [11]. Up until 2050, if consumers continue the energy waste, it is possible that 8% of the electricity demand in the world comes from the use of electrical appliances on standby. However, there are technologies available to reduce this demand in domestic equipment [17], [18].

The work that has been developed in this thesis is intended to produce new contributions through the formulation of mathematical models and prototype developments, aiming for a smarter and sustainable system though energy efficiency improvements.

The sustainable exploitation of these resources is crucial to ensure the development of all society and to allow them to satisfy the needs of present generations and future generations. From the analysis of the literature review carried out during the research work, there are several challenges to reduce electricity consumption, namely:

- Reduction of fossil fuel dependency and mitigation of greenhouse gas emissions;
- Eliminate the barriers, such as the lack of regulation in a given area, or to make adjustments to the consumption of a particular energy source;
- To increase energy efficiency by acting at the level of equipment and control systems;
- Creating methods to make a more intelligent and sustainable system.

In summary, it is important in the context of industrial engineering and management to develop innovative ways to manage and control electricity. The following research topics are addressed in the forthcoming chapters:

- The approach developed for new type of consumer load in the electric power system, Electric Vehicles (EVs), Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) options, instead of peak power procurement from the grid.
- The development of an innovative form to control the loads in order to optimize energy consumption in the residential sector, whereby facilitating the consumers by providing complete information about their energy consumption and respective cost.
- The development of a system based domestic load energy consumption monitoring prototype device, as part of an Advanced Metering System (AMS).

1.2. Motivation

The advancement of the human race has been driven to a great extent by the innovation, expansion, and diffusion of new technologies, which play a central role in modern societies by enhancing social welfare and defining new ways for humans to interact with their environment.

In the last century, humans achieved unprecedented levels of comfort and wellbeing. Naturally, this progress was due to the large scale introduction of technologies in all aspects of human existence. However, the exploitation of our resources is not sustainable, and if we continue the consumption of energy at the current levels, then it may cause the end or at least a pause in the prosperity cycle we have been accustomed to since the beginning of the last century. Besides, our society faces serious challenges which jeopardize our model of economic and social development. As a consequence, mankind has to find a way to rationalize existing resources. Society is gradually getting older; we are witnessing the growth of an aging population and a significant reduction in the birth rate.

Given this scenario, within medium and long-term horizons, countries will not be able to afford the expenses since this is going to place a huge burden on the health care systems, and the pressure and demands on the health care providers will increase. [19] Therefore, medical care for the elderly has become a major health and ethical issue and a critical part of government policy. On the one hand, we have an unsustainable pattern of energy consumption and, on the other hand, we have an aging society. In recent years, a new paradigm that allows people to manage consciously home energy resources and to improve their behaviour in order to reduce energy consumption is the “smart home”. This concept, which could be the answer to the challenges stated previously, has gained importance due to four main factors [20]:

- The fast progress and miniaturization observed in semiconductor technology resulting in the proliferation of computing and electronic devices in our everyday lives;
- The exponential growth of Microcontrollers Unit (MCU’s) processing power;
- The integration of advanced signal conditioning in very small sensor nodes that can measure and store data using complex processing techniques;
- The rapid development and progress of wireless technologies, essentially short range and low power applications.

As life expectancy has risen significantly over the last century, and people enjoy more satisfying lives, they desire as much independence as possible.

However, autonomous lifestyles bring new demands and challenges. One is a constantly aging population and the other is the unsustainable habit of energy consumption; both require new ways to manage this apparently impossible problem.

The smart home concept is based on the interaction between services and features [21]. This idea results from a convergence of several areas: entertainment, security, energy management and health care. However, the smart home paradigm can be the answer to such demands since the residence is equipped with technology that observes the inhabitants and provides proactive services that can deliver comfort, security and safety, energy saving and sustainability, and home care.

The deregulation of the electric power industry is a concern of investors and other participants of the electricity market for more than a decade with the aim of obtaining a more efficient use of electric energy and improved profits. As a recently growing concept for an effective deregulation of the electric power industry, the smart grid framework has drawn significant attention from developed country governments [21].

The smart grid is a vision for enhancing the efficiency of electricity utilization from the production to end-user points, together with effectively accommodating all generation and storage options and enabling consumer participation in the demand-side. Coupled with the growing importance of the smart grid vision, smart households that can monitor their use of electricity in real-time and act in order to lower their electricity bills have also been given specific importance by the research, regarding possible demand-side actions [22]. Demand side actions for smart households in a smart grid generally focus on Demand Response (DR) strategies, allowing interaction between utility and consumers.

DR is a term defined as "*changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*" by the US Department of Energy (DOE) and comprises *incentive based programs* and *price based programs* (time-of-use, critical peak pricing, dynamic pricing) [23].

The utilization of DR strategies can be considered mature for industrial customers, but this is a relatively new concept for residential households responsible for nearly 40% of energy consumption in the world [24]. There are many enabling technologies for DR activities in residential areas. Especially, Home Energy Management (HEM) systems and smart meters have the leading role in effectively applying DR strategies [25]. With the introduction of different kinds of electric loads in the market, the load shapes of households have started to change significantly. As a new type of end-user appliance/load, EVs have recently gained more importance, as the electrification of the transport sector, which traditionally is a major fossil fuel consumer, is a topic of current interest [26]. Electric vehicles have a different structure with challenges and opportunities that should be examined in detail.

Energy needs of electric vehicles as a load can reach to the levels of new power plant installation requirements. The recommended charging level of a Chevy Volt, a small sized EV, is 3.3 kW [27], which can even exceed the total installed power of many individual homes in an insular area, for instance. Besides, electric vehicles can also be employed as a resource, especially during peak periods with the possibility of V2H and V2G options. Growing concern about energy consumption is promoting the better usage of energy resources at different levels of human activities. It is a fact that the domestic sector has an increasing impact on the world’s energy consumption. As an example, in the European Community space heating energy needs account for about 70% of a typical home electricity bill, followed by water heating, which accounts for 10% [28].

Despite continuous improvement efforts made by domestic equipment manufacturers, appliances such as refrigerators, space heating/cooling systems, water heaters, clothes washers, dryers, lighting, and dishwashers continue to burden household energy bills. Moreover, appliances based on non-linear loads are continually increasing with the mass production of electronically operated devices. So, their impact on electricity energy consumption is tending to grow over time. Recent studies argue that it is possible to accomplish energy savings of 30% when energy efficiency measures are implemented [29]. Different strategies are being planned towards electric network transformation into smart grids, and tariff schemes based on demand response programs that call for a paradigm shift in terms of domestic energy consumption habits, or by technological interventions at the level of alternative control techniques for reducing electric energy consumption in the normal usage of domestic appliances [30].

Whatever the approach followed, home advanced metering systems will be part of this revolution, providing an advanced monitoring capability, easy interaction with the home user and flexible management options that facilitate domestic load scheduling according to daily needs in order to achieve energy savings with a positive cost-benefit ratio. At the core of any home energy management system, the metering infrastructure relies upon a network of power meters [31].

In this context, a 2.4GHz ZigBee based distributed home energy metering system represents a viable option. Its main functionalities as well as the technical details behind the power meter design are discussed in this thesis. The Radio Frequency (RF) link is ensured by pre-manufactured boards equipped with a wireless transceiver. Also, a custom analog front is designed taking into account specific requirements for voltage and current measurements, namely signal acquisition and filtering [32]. Moreover, a power meter prototype is projected for acquiring, processing and computing the main electrical quantities used for quantifying an electrical load connected to an alternate current low voltage system, such as the root mean square voltage or current, active and apparent power, along with the load power factor [33].

Residential buildings are among the largest energy consumers corresponding to 31% of global energy demand [34]. Direct measures are already being implemented, such as a regulatory framework recommending new buildings to follow strict construction rules as for building materials. Other measures are intended to promote new energy consumption habits through a dynamic electricity pricing scheme as a part of Demand Side Management programs. At transnational scale, further coordinated actions are proceeding to address energy efficiency challenges [35].

Typically, in a residential house the loads that contribute most for the energy bill are air cooling and heating equipment for human comfort, water heating for personal hygiene, along with the indispensable refrigerator. For the European residential sector, estimates indicate that 75% of the energy consumed is for water heating and cooling purposes [36], while the average share in the US is 40% [37].

There are two generic approaches for energy consumption management at residential level: reducing load usage or shifting consumption. Shifting consumption is actually a technique related to demand-side management, as discussed in [38] and [39].

The aforementioned approaches, while effective to reduce energy costs, might not be totally compatible with the daily needs of the residents. Hence, alternatives can be found by evaluating complementary forms of temperature regulation in this class of loads.

Conventionally, the majority of this equipment's ensure thermal regulation by an ON-OFF power mechanism known as thermostatic control. Alternate control techniques are being investigated in order to address energy rational utilization of electric loads of appliances in a home, such as residential energy monitoring and management based on fuzzy logic [40], PID control, artificial neural networks, Model Predictive Control (MPC), among others [41].

Many researchers use as instrument the MPC, which can improve system performance through a model-based predictive control [42]. The MPC technique has become a valid tool since its inception in 1970s to solve complex industrial processes with many control variables, due to its ability to handle hard constraints on control and states [43].

Instead of performing corrections only after errors take place, MPC uses the model of the loads to anticipate the future evolution of the system. Thus, future control inputs and future plant responses are predicted in advance using the system model and optimized at regular intervals with respect to a performance index [44], [45].

A general approach for MPC control implementation in the building sector is to improve building thermal comfort, decrease peak load, and reduce energy costs [46].

Normally, it addresses Heating, Ventilation and Air Conditioning (HVAC) systems to minimize energy cost beyond a mere reduction on energy usage [47]. Finally, other implementations aim to enhance flexibility of thermal energy storage cooling systems [37], [48].

1.3. Research Questions and Contribution of the Thesis

This thesis aims to investigate the potential enhancement of electricity utilization efficiency through home energy management systems within the smart grid framework.

In particular, the following research questions will be addressed:

- What are the requirements of the Home Area Network (HAN) in the application areas that can benefit from this integration?

- How the evaluation of dynamic-pricing and peak power limiting-based Demand Response (DR) strategies is made with a bi-directional utilization possibility for Electric Vehicle (EV) and Energy Storage System (ESS)?

- The new developments of mono-phase power measuring systems can enable advanced measurements in the domestic sector?

- What is the impact of MPC and other optimization technologies on energy savings of residential households?

The contribution of the thesis may be summarized as follows:

- A thorough discussion of four distinctive functional service areas and the analysis of wired HAN requirements.

- To include the capability of utilizing EVs as a storage unit via Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) options instead of peak power procurement from the grid.

- The development of a system-based domestic load energy consumption monitoring prototype device as part of an Advanced Metering System (AMS).

- The development of an innovative form to control the loads in order to optimize energy consumption in the residential sector, whereby facilitating the consumers to provide complete information about their energy consumption and respective cost.

1.4. Thesis Structure

The structure of this thesis is divided into six chapters, each consisting of multiple subchapters. Here the chapters will be depicted in order to give a general idea of how it is organized in order to help the reader.

Chapter 2 presents the state-of-the-art related to the innovative contributions made by the scientific community with the new technology of the smart home. Also, it presents the characteristics of wireless protocols in order to determinate the strengths and weaknesses of each of the communication protocols. Moreover, with the knowledge of these characteristics, it is possible to integrate the communication and collaboration capabilities of various systems and devices within their habitats to reach a common goal.

Chapter 3 addresses demand response strategies for the optimum appliance operation of smart households. This chapter also presents a methodology based on a mixed-integer linear programming (MILP) framework based modeling of a Home Energy Management (HEM). Also, it presents the impacts of different EV owner consumer preferences together with the availability of ESS and two-way energy trading capabilities on the reduction of total electricity prices. Finally, it presents the comparison of different case studies.

Chapter 4 presents an energy metering system integrated on a home communication architecture. Also, it demonstrates the distributed metering system and describes the details of the wireless watt-meter prototype developed. This chapter also presents an experimental characterization of power meter devices and finally it presents concluding remarks.

Chapter 5 addresses the underlying mathematical modeling of the operation of the MPC controller that was used, which is derived for the specific case of this chapter. Finally, relevant simulations and the results obtained are presented.

Chapter 6 presents the main conclusions of this work. Guidelines for future research and contributive works in these fields of research are provided. Moreover, this chapter reports the scientific contributions that resulted from this research work and that were published in journals, as book chapters or in conference proceedings.

1.5. Notation

The present thesis uses the notation commonly used in the scientific literature, harmonizing the common aspects in all sections whenever possible. However, whenever necessary, in each section a suitable notation may be used. The mathematical formulas, figures and tables will be identified with reference to the section in which they are inserted. Mathematical formulas are identified by parentheses (x.x) and called “Equation (x.x)” and references are identified by square brackets [xx]. The acronyms used in this thesis are structured under synthesis of names and technical information coming from both the Portuguese or English languages, as accepted in the technical and scientific community.

Chapter 2

Smart Home Communication Technologies and Applications: A Review

This chapter discusses Home Area Networks (HAN) communication technologies for smart home and domestic application integration. The work is initiated by identifying the application areas that can benefit from this integration. A broad and inclusive home communication interface is analysed using key piece a Gateway based on Machine-to-Machine (M2M) communications that interacts with the surrounding environment, the main wireless networks are thoroughly assessed, and later, their suitability to the requirements of HAN considering the application area is analysed.

2.1. Smart Homes

2.1.1. Introductory definition

Smart home definition and its functionality goals have evolved continuously due to the fast evolution of diverse technologies, emerging from the research activity in home automation related technologies and from home networking developments. There is a low level of scientific consensus on the subject of "Smart Home" definition. Thus, several authors disagree on what is characterized by this term and what is or not part of it [49]. A smart home is described by Silva *et al.* [49] as a "*home-like environment that possesses ambient intelligence and automatic control*" capable of reaction to the behaviour of residents and to offer various accommodations and is further divided into four types of smart homes: healthcare based, multimedia and entertainment based, security based and energy efficiency based smart homes a definition which is supported by Zhang *et al.* [50], and Pedrasa *et al.* [51], among others.

Following the line of concepts developed by the authors above, Smart Home is the backbone which will enable the management and control of different areas of a residence binding in four pillars of human livelihood inside a house.

From the last idea, such pillars are: comfort and welfare, physical integrity and facilities' safety, rational management of domestic equipment's energy and the possibility to provide healthcare services to its inhabitants. The critical aspect for this backbone to work is to possess a cheap, reliable and easy designed structure of communication [52]. Therefore, Smart Home can be defined as a concentrator, disseminator of information and services that intends to cover the totality of a home's functional areas, being operational not only for the particular elements that are in the house in order to improve the levels of comfort and quality, but also to provide a gateway or interface to the exterior by the means of an interaction with other paradigms such as smart grid [53], [54], [55] and smart city [56] which will originate the ability to share all the managed information with external elements. Smart homes will radically change the way that people interact with each other and how they manage their private lives. As a result, people will start to play an important part in this effort by adding technology to domestic management, which in turn will support them to limit energy waste and also to receive health services that are, at present, centralized and provided by hospitals [57].

2.1.2. Home Application Areas

The Smart Home has been of interest to researchers over the last 30 years. Several studied this topic which has branched out into a wide variety of applications. According to the literature, the smart home will enable the management and control of different areas of a residence [49]. Four distinctive general functional areas of service can be classified, which are [58], [59], [60], [61]: (a) Energy Efficiency and Management; (b) Health Care; (c) Entertainment; and (d) Security.

2.1.3. Energy Management

Households use one of the major parts of the world's energy and more than half of the energy consumption in homes comes from electricity [62]. The central task of energy management is to reduce costs for the provision of energy in households and residential building facilities without compromising the user's wellbeing. The functions of the home energy management are:

- Controlling activation/deactivation of home appliances;
- Collecting real-time energy consumption from smart meters and power consumption data from various household appliances;
- Generating and monitoring a dashboard to provide feedback about power usage, providing control menus to control appliances;
- Providing a universal link to the broadband Internet [63].

The overall improvement of a house's energy efficiency is urgent. A need to increase energy efficiency of appliances was identified by many researchers and amidst numerous approaches to do a smart home was deemed as a serious answer to this challenge. Emerging trends, developments and paradigms in smart environments such as Smart Homes are frequently based on smart devices and equipment, such as smart meters which can manage and monitor through a network the home energy consumption [64].

The aim of an energy efficiency driven smart home is to allow the network elements to dynamically work together and make their resources available, with the intention of reaching a common goal, i.e., the energy saving of a house. A few key features that apply to various energy efficiency driven Smart Homes are [65]:

- The available node energy, which is frequently limited, i.e., a battery supplied nodes, which work with limited amounts of energy.
- Smart devices and equipment, which are able to offer the opportunity to monitory and to remotely control key features within homes.

Decision-support tools have been designed to assist users in making smarter decisions and are based on getting the most out of the benefits gained by the end users when users use energy saving services. In this sense, it becomes necessary that at the same time with the energy management challenges, a proper communication protocol between smart devices would regularly improving the system performance. The proposed energy efficiency driven smart home systems by the literature are based on task assignment, integration of various physical sensing information and control of various devices. However, such approaches are not concentrating or designed on finding the best communication protocol between devices that would translate to an improvement of the overall system performance [65].

The aforementioned topics have been handling by different authors using diverse views about how improvement of household's energy efficiency can be done, which resources should be use and what system architecture is desirable to implement. Some researches make a reference to Smart Home Energy Management Systems (SHEMS) — which is capable of reducing the total electricity bill for consumers and simultaneously flatten demand peaks [66] while others researchers call it as Home Energy Management System (HEMS) [67].

Peruzzini *et al.* [68] proposed a methodology to improve smart home information management by promoting device interoperability, and network collaboration for energy efficiency aims to overcome the main issues of existing smart homes by mapping the devices' functions and data, correlating the devices' functions with the smart home actions, and defining what information to send/receive to propose energy-control services.

However, since the accidents in power security occur frequently, Ma *et al.* [69] proposed to ensure the security of household electricity appliances, designing a power security system based on stream data mining. Han [70], and Lim [71] presented a smart home energy management system using Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 and ZigBee protocol by integrating diversified physical sensing information and control of various consumer home devices, with the support of active sensor networks having both sensor and actuator components.

Hu *et al.* [16] present a hardware design SHEMS with the applications of communication, sensing technology, and machine learning algorithm so consumers can easily achieve a real-time, price-responsive control strategy for residential home loads such as Electrical Water Heater (EWH), heating, ventilation, and Air Conditioning (HVAC), Electric Vehicle (EV), dishwasher, washing machine, and dryer machine.

Cherchi *et al.* [65] proposed a framework through M-Bus communication system that aims to manage the energy consumption of controllable appliances in groups of Smart Homes belonging to the same neighbourhood. Also, it was proposed a lightweight algorithm with the purpose to share the available alternative power between the houses.

2.1.4. Renewable Energy Management Driven Smart Home

The universal concept of an energy management driven smart home could include the use of solar, wind and/or other renewable energy sources with an intelligent power consumption mechanism for the electric appliances placed inside the house and a collaborative smart grid to ensure the interconnections between them [72]. With the use of advanced metering and display technologies in an established smart home, the user or the system itself is capable of lowering the energy consumption or postponing the energy demanding operations concerning the present electricity price by managing the household electrical features and under the condition of ensuring a positive comfort level [73].

Nazabal *et al.* [72] proposed an Energy Management System that includes renewable energy sources for the efficient use of the power created by a Smart Home and the power consumed by the electric appliances of the house with an overall system description, from software protocol to the employed hardware. Tascikaraoglu *et al.* [73] proposed an experimental smart home with several renewable energy sources and storage systems in terms of various aspects such as appliances control, in-home energy management and power flow. Additionally, the study embodies one of the very first challenges to assess the contribution of power forecasting of renewable energy sources on the performance of smart home concepts. Al-Ali *et al.* [74] presented the design, implementation and testing of an embedded system that integrates solar and storage energy resources to a smart home. It was designed by utilizing a controlled load bank to simulate scaled random real house consumption behaviour.

2.1.5. Health Care Systems

Having advanced technologies in homes will lead to various opportunities in the near future in this area. One of the most important is the monitoring of a person's cognitive and physical health and, as a consequence of an aging population an area of critical needs is eldercare. The health smart home concept, which can meet this challenge, has been extensively researched by many authors as described in [75].

Suggestive kinds of smart healthcare technologies contain simple devices such as blood glucometers, oximeters, blood pressure monitors, among others, which deliver standardized outputs for specific physiological conditions, smart applications or some software able to analyse and process the body signals, sensor integrated in smart devices (gaming devices, smartphones and pads), wearable sensors (e.g., wrist straps, T-Shirts) and additional devices entirely manufactured for the purpose of body signal monitoring/processing (e.g., mainframe computers, tablets, among others) [76].

The aforementioned proposed solutions can be applied to several healthcare technological solutions, including smart homes. Each of these categories poses different challenges when their designers trying to comply with the Health Care Smart Home requirements. The patients utilize components (e.g., sensors), which may be invisible and transparent to the patients coupled with its constantly increasing storage and communication capabilities, their small size enable collection, processing, and potential disclosure of personal health information. Whether at home, work or traditional settings (physician's office, hospital), healthcare information technology infrastructures transfer sensitive patient health information and as consequence this issue faces several constraints and information security threats. Security safeguards, controls, data quality and integrity are classified as top priority, mostly because they arise by different fields of information security, but protecting the patient's location and purpose specification, remain the least addressed requirements [77].

Suryadevara *et al.* [78] reported a mechanism for the estimation of elderly well-being condition based on usage of household appliances. Brulin *et al.* [79] proposed a computer vision-based posture recognition method for home monitoring of the elderly; while Wang *et al.* [80], implemented an enhanced fall detection system based on on-body smart sensors that successfully detect accidental falls in a consumer home applications. Junnila *et al.* [81] proposed a general purpose home area sensor network and monitoring platform intended for e-Health applications. The outdated devices commonly used to monitor body parameters like heart beat rate or exertion level are not fit for real-time measurements [82].

Nonetheless, a continuous monitoring, of such parameters as diabetes, hypertension, and cardiac diseases could allow for constant control of elderly people's physical conditions and provide valuable information since these chronic diseases are more common among this age group [61].

2.1.6. Advanced Multimedia Services

Media consumption within the home has been growing over the years and new forms of domestic entertainment are very popular, always changing how society acts and relate. Such category of smart home shows the enormous development potential. A main promoter for the evolution of future Home Area Media Networks (HAMNs) is the emergence of beyond High Definition (HD) media formats. These formats oblige for greater demands on networks and for lower latency, high-capacity and rigorous Quality-of-Service (QoS) in comparison with other existing formats [83].

Furthermore, such related data intensiveness will require a real–time interconnection of multiple, probably distributed, of high performance media processing and storage resources. In order to be able to satisfy this features and demands, novel networked architectures are required. Ultra-High-Definition (UHD) embodies the next generation of digital media i.e., past High Definition (HD) as 4K and 8K have four (4096×2160) and sixteen (7680×4320) times the spatial resolution of HD, respectively [84].

As a result, large-scale networked circulation of UHD contents demands with high bandwidth interconnections is normally found in optical networks. UHD formats are also data intensive and, as consequence, it results in a direct correlation with the quantity of processing capacity that it is necessary. Furthermore, high performance media processing resources and high capacity networked storage are also required for large-scale UHD HAMNs. Additionally, there is a paradigm shift headed for user-centric HAMNs [85].

The purpose of this paradigm is to set-up flexible customizable network-based media communication platforms that support distinct media users and tools. In addition, it allows the creation and generation of new media content and services on-the-fly, and supports the transmission of content across several media and network environments [84], [86]. Li *et al.* [59] developed a framework for resource allocation in a Cognitive Digital Home (CDH) with a multiplicity of Radio Access Technologies (RAT) such as cognitive radios and legacy radio devices supporting heterogeneous applications. Yu *et al* [87] designed and implemented an integrated architecture that supports the outdoor remote control to home devices and the sharing of digital media among indoor and outdoor devices.

Yu *et al.* [88], proposed a smart furniture prototype for the smart home, a magic mirror table that has a camera to capture the viewer's facial expression. The system is able to determine the emotion of the viewer and then act accordingly to alleviate your emotion.

2.1.7. Surveillance and Security

The implementation of communication technologies for essential surveillance and home automation leads to a wide range of opportunities as well as technical challenges. Surveillance and Security Systems require a robust configuration in order to collect meaningful, reliable, and accurate data [89]. As a result, such systems do have a need for adequate support for the QoS required by the delay-sensitive and bandwidth-intensive multimedia data that currently do not display.

These restrictions do not significantly impact delay-insensitive data acquisition but can have considerable consequences for the real-time surveillance or monitoring applications as often lead to insufficient or improper measurements and erroneous event detection. Real-time multiuser multimedia applications like monitoring or surveillance, which use multiple cameras, have being recently begun to be proliferated over flexible and low-cost multi-hop wireless networks. In these types of multimedia systems, several sources share the limited network resources and together transmit the captured video streams to a remote central monitor as described in [89].

There are many recent studies dealing with security issues in a smart home infrastructure. Komninos *et al.* [90] classified the main risks of interaction between entities in a smart home and smart grid environments and proposed promising security countermeasures given the specific security goals. Kim *et al.* [91] proposed a smart system using both face recognition and sound localization techniques to identify foreign faces through a door phone. Lian *et al.* [92] proposed a smart home safety handwriting recognition technology to confirm user identity and to manage door security using a recurrent neural network with associative memory. Li *et al.* [60], considered the architecture and design of a secure access gateway for Home Area Networks (HAN), so that real-time secure monitoring and control of the devices could be achieved through a smart phone.

2.2. Home Area Network

2.2.1. Home Communication General Architecture

A smart home can function to a certain extent in an interactive and independent way. These additional capabilities can then be used to improve the quality of life within the household in various respects, such as automation of routine tasks, provision of health services, rationalization of energy consumption, improved individual efficiency, and enhanced home security, as well as to revolutionize what we define as entertainment [93].

Since smart home interconnection specifications and communication technologies are relatively new and under development, most available communication protocols were developed prior to the advent of the smart home vision. Consequently, evaluation studies are critical to determine whether these protocols are suitable for smart home communication requirements. Thus, intense research has been devoted to this field [94]. In this context, local networks for small home areas are gaining more presence and relevance as advanced automation and energy management functionalities are added to household devices. Essentially, the HAN-enabled smart home is a fundamental step to enable the exchange of information and interoperability among several smart domestic appliances connected to other devices or networks through many protocols, such as Bluetooth, ZigBee, WiFi, Z-Wave, among others, inside or within the close neighborhood of a house [95].

The modern home local wireless networking approach is based on standards such as Local Area Network (LAN), Body Area Network (BAN) or Personal Area Network (PAN), which are used to describe a network of a smaller scale ranging from 12 to 100 meters. Commonly, such approaches target local network applications based on low cost wireless technologies. PAN and BAN communication infrastructures are largely employed in domestic applications allowing the user to be on the move, and do not require high expertise to manage the network operation, such as adding or removing components [96]. Although some services like the monitoring of certain features related to health issues, and performed by smart homes, such perspectives can be included in the BAN range of communication, where a wider area of action is required for the whole infrastructure of operation. Nonetheless, such network configuration can be sufficient since it is capable of staying fully operational for a long time and its energy is cost effective [96].

PAN [96], [95] can fulfill more requirements since it consists of wearable and portable equipment capable of interacting with the immediate neighbourhood and it is able to communicate with the wider environment via larger area wireless backbones. Additionally, wireless sensor networks (WSN) are alternative cost effective solutions for connecting sensor nodes in highly meshed networks with very low energy requirements [95].

Even though such categories of networks cover a broad range of functionalities, this is insufficient. In addition, there is no interoperability feature that could allow communicating with each other. Therefore, a wider network (global wireless infrastructure) is required to congregate different levels of communication that have specific complexities such as timing constraints or critical data traffic of high priority [97].

Figure 2.1 shows the general framework of the smart home integrating main application areas, showing that security, health care, entertainment, energy efficiency, and all related services are connected to a domestic communication infrastructure. Taking into account the different purposes of each of these areas, a global network is required for an integrated higher structure of communication that comprises several dedicated home networks.

The interoperability between the different applications relies on a universal multi-purpose home gateway that acts as communication protocol translator. It is actually a data aggregator that processes data traffic coming from different home networks, independent of the means of physical transmission, i.e., wired or wireless. However, the gateway connects the Smart Home data communication infrastructures with the outside world [98].

The connection can be routed to a mobile network or through a cable based infrastructure. At the upper level, the data is forwarded to a cloud system where it is classified, organized and stored for different purposes and aims. In turn, their access is provided to specific entities such as a smart grid [54], smart city [56], and smart healthcare network, which will make sharing all the managed information with external elements possible.

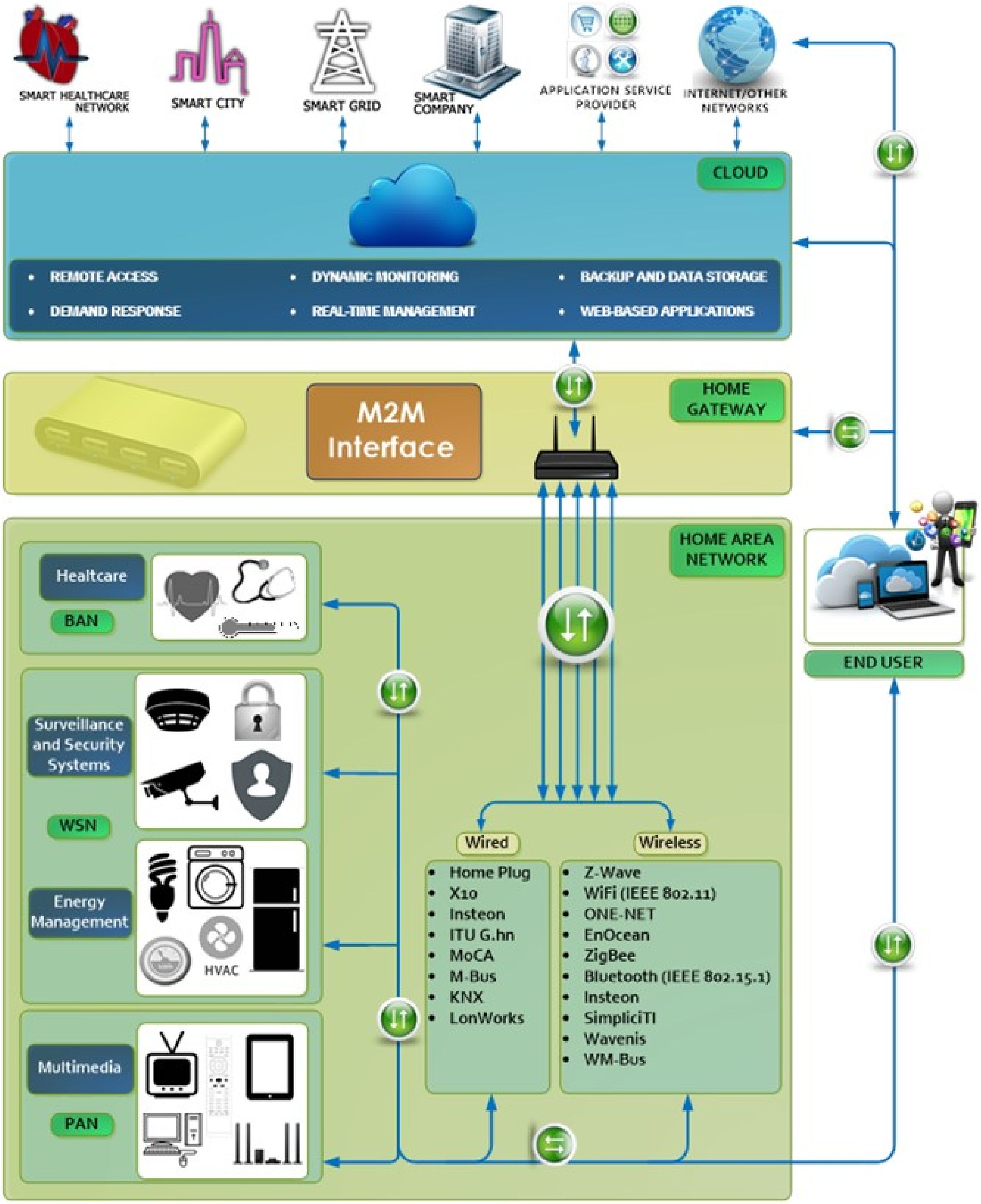


Figure 2.1. Smart home devices accessed through global network framework.

2.2.2. Home Gateway with M2M Interface as Enabler for Smart Home Services

M2M refers technologies that can enable both wireless and wired systems to interact with other devices of the same nature and where one device generates events and the other interprets them. Among a wide range of possible applications at the early development of M2M, smart homes have the highest market potential for the reason that it is closely related to human life [99], [100]. Along with the growth of M2M related technologies, Wireless Networks (WN) are in the process of being applied to smart home systems, therefore, enabling a greater ability for devices and a more reliable and richer function of the smart home system [101].

M2M wireless networks can help to increase the production and efficiency of machines and improve the safety and reliability of complex systems [102]. The main concerning issues in these M2M service networks come from the vertical fragmentation and complexity of M2M markets. This complexity is as a result of the number of connectivity means, embedded devices, and service platforms — particularly of their heterogeneity [103].

2.2.3. HAN Oriented Cloud

Cloud computing has just emerged as a new paradigm of ubiquitous computing and has been one of the utmost significant improvements in computer technologies and industry in recent years. The development of cloud computing expands the capacity of computer calculation and the convenience for the users [94]. Though home automation technologies already are commercially available, they are essentially intended for signal-family smart homes with a high cost, and are alongside the continuous development of digital appliances in smart homes.

There are many benefits of introducing two-way communication of the smart home HAN with a cloud based system, since information of the house's expected electricity usage comportment is concentrated and made available to a utility, load serving entity or an aggregator. Therefore, these entities are able to execute their optimization processes by ensuring precise information of their consumers. Another significant feature is that the end-user could remotely access with a smartphone, data regarding electricity consumption or even set parameters to the HAN in real-time [104].

Moreover, the computational resources part of HAN in a domestic environment are systems that might have reduced capacities of storage and computational power, which in case of data being stored in a local database or a Personal Computer (PC), the risk of losing the data or it being corrupted by third parties may possible as explained in [105].

2.2.4. HAN Internet Protocol (IP)- Based Solutions

Regardless of the initial doubt shown by many researchers about the suitability of the Internet architecture for wireless networks, nowadays good performing implementations of IPv6 stacks exist already for HAN. In addition, IPv6 presents solutions prepared for network statelessness and auto-configuration, and satisfies the great address space needed for such networks. At the same time, the Internet Engineering Task Force (IETF) has been developing the standardization of mechanisms in order to encompass the Internet for actuator and sensor networks.

In addition, the utilization of IP for such type of devices is being endorsed by the recently created IP for Smart Objects (IPSO) Alliance. Despite the fact that the work prepared by the IETF is at present in progress, IP-based sensor networks are emerging and could radically increase the capillarity of the Internet. In the near future, entirely standardized IP-based solutions for wireless HANs will be possible and accessible [106].

2.3. Smart Home HAN Requirements

The communication requirements related to HAN are defined by the services and applications which run in the household; for example, diverse processes have to be executed among all devices in a smart home network. According to this condition, HAN have to provide reliable communication between application area devices and from the functional area devices to HAN devices for different indoor scenarios. If it is the case, then, all HAN devices have to be dependably accessible as well [50]. Communication can be seen from the general and individual point of view. Therefore, it is important to identify what is needed to ensure an efficient exchange of information in a functional area.

However, since it is available more than one functional area in the same physical space of a smart home, it is required to find a way for all systems coexist in a superior infrastructure of communication inside of the same infrastructure [96]. It may not be advantageous and economical to have identical communication requirements for all smart home appliances; for example, a temperature monitoring device needs only low speed communication infrastructure, whereas facial recognition communication infrastructure needs more speed communication. Next, the organization and classification in four sections of main characteristics and requirements for HAN is briefly described [107], as shown in Figure 2.2.

2.3.1. Secure Communication

Home data networks are increasingly exposed to external attacks from the internet. At the same time, near local networks inside or outside of the house may be used to get access to sensitive information such as data metering or to change the dose of diabetic medicine endangering the lives of their residents [108].

This means that the HAN has to authenticate all devices, protect data integrity and privacy (e.g., by encryption) and provide protection against replay attacks. Such attacks are a particular concern where the HAN is used to support a security related application (people and/or property). HAN connected devices may have very limited resources to achieve low cost and long battery lifetime [109].

This is the case of wireless HAN tailored for portable devices used, for example, to monitor patient health state or for tracking packages with restrictions such as antibiotics. As for networks based on physical cables, Ethernet enabled devices have enough hardware resources for accomplishing the security issue. Despite the physical and energy constraints advanced security services are expected to be provided by the wireless HAN technology and the platform operators [110].

Security is one of the most significant characteristics of any system. Researchers have different perspective regarding security and it can be defined in many ways, for instance, the US department of commerce defines security as a condition that results from the creation and maintenance of protecting measures that guarantee a state of inviolability from hostile acts or influences [111].

Figure 2.2. The classification of the main characteristics and requirements for HAN.

In general, security is a concept similar to safety of the system as a whole. Thus, its intention is to defend HAN area of attacks such as: data modification, impersonation attack, eavesdropping and replaying. The security requirements are:

- Integrity

It certifies if a message that is being sent reaches the receiver intact. It is important that this is done in an effective and accurate manner. If this does not happen the receiver equipment can be unutilized, damaged or even a message could be sent to the wrong receiver by the source. Falsifying message contents, including the sender's address, has to be detected. The sender of a message must be able to prove that a specific message has been sent and if the receiver has indeed received the message. Nobody can falsify the network operators in terms of usage fees and the network operators can only charge fees for successfully delivered messages [112].

- Authentication

Authentication is known due to its three major aspects. Entity authentication helps to verify the veracity of a claimed or presumed identity of the sender. Data origin authentication verifies the source of the message. Location authentication guarantees the truthfulness of the claimed or presumed location information. This requirement is utilised by one node to identify another node or to verify the source of origin of data in the network. Thus, it is essential for tasks like association, beacon, parameterization, and sending and/or receiving of critical data for the adequate operation of the involved network's elements [113].

- Confidentiality

Message contents must be kept confidential, which means that only the communication partners may comprehend it. The messages of the sender and/or receiver should be indecipherable for everybody else, and third parties, such as the network operators, should be incapable to perceive their communication. Furthermore, potential communication partners or third parties cannot be capable to locate HAN stations or their users [107]. This can be achieved by generating the information incomprehensible by using cryptographic encryption. As the information travels across the home networks, data must be ensured to prevent non-authorised access from other elements. In this sense, data encryption allows a high level of protection by masking the information whose reading requires a key for that purpose. The communication technology shall provide native mechanics with adequate strength and encryption method, as recommended for example in RFC3565 for AES128 [114].

- Security Certification

The HAN operated communication must support device security certification. Each device model must be security-certified by a recognized independent authority, as described in [50], [96].

2.3.2. Network Operation

Network operating systems provide access to network resources for user processes. This is required to realize the following objectives:

- Interoperability

The interoperability and completeness of the infrastructure strongly affects the effectiveness and efficiency of the overall performance of the system. Smart home elements involve a number of common and interoperable standards for communications purposes. To integrate the various technologies and communications protocols, this kind of capacity is desirable with the aim of mutual recognition and offering continuous data transference. Inefficient or deficient integration and interaction among elements could delay the response time and also damage the global system’s throughput and operation [115].

- Ad Hoc Deployment

Since it is important for different network devices to be deployed in a non-structured mode and spread through the house, several wireless HAN applications lack the requirements to predetermined locations of individual stations. Nodes have to perform many setup and configuration steps autonomously. Those steps should incorporate the establishment of communications with near sensor nodes and find out their positions in order to start their sensing responsibilities. The information available directly affects the variability of the mode of the sensor nodes’ operation [96].

- Self-Management

Various sensor network applications are programmed to operate with no infrastructure support or the prospect of maintenance and repair. Consequently, in order to configure themselves, operate and collaborate with others, adapt to failures events, and the changes in the environment or environmental stimuli, it is required that sensor nodes should be self-managed, which means that sensors must be completely independent of human intervention [116].

- Maintainability

Maintainability is a requirement that essentially reflects how durable and reliable the HAN is. The environment can change, which means depleted batteries, failing nodes and new tasks. Thus, HAN units have to monitor their own health and status in order to change operational parameters or to choose different trade-offs, such as providing lower quality when energy resource becomes scarce.

In order to repair quickly and cost-effectively the various devices and communication components, the HAN must be designed for the purpose of an easy maintenance [117].

2.3.3. Dependability

Dependability attributes are applicable to these systems with reliability, availability and resiliency features [118]. The reliability, availability and resiliency of externally-managed cloud computing resources continue to become an appealing choice for many home-dwellers without interest or experience in IT. The dependability requirements are [102]:

- Reliability

Reliability can be defined as the probability that a network functions continuously and properly in a time period interval. A reliable network is a network that is capable to unceasingly deliver an accurate service. Reliability can be categorized into different levels: event reliability, packet reliability, Hop-by-Hop reliability, and End-to-End reliability [102]. Both packet and event reliability levels operate with the required quantity of information to notify the sender of the occurrence of an event within the network environment. End-to-End and Hop-by-Hop reliability levels are related with the successful recovery of the event information. Still, all of them rely on redundancy and retransmission mechanisms [119].

- Availability

In the traditional definition, a network is considered highly available when its downtime is very limited. The purpose of the availability is to guarantee that the services of network are always available and will still operate either when few failures occur or to operate quick restarts when failures take place [120].

- Resiliency

The resilience defines the recoverability and fault tolerance of a network. Due to some intrinsic features, wireless mesh networks are more vulnerable to possible node and link failures when compared with wired networks.

Consequently, the resilience to failures has become a very significant issue recently in the design of wireless mesh networks [121]. It has been also noticed that sensor nodes misbehavior can origin failures as well, and thus have driven new challenging and open problems to the resilient wireless network design, weaken the performance and even the whole connectivity of the networks.

When incidents occur, the degree of resiliency defines how trustworthy the HAN can truly be. It clarifies, mainly from a safety and security perspective, the capability to restore and recover from a range of disruptions or malfunctions through the robust fast-response process, especially the vulnerable digital elements in the house [122].

2.3.4. Energy Optimization

Home Area Networks provide energy monitoring, controlling and energy consumption information about the appliances and devices, and hence support energy usage optimization by allowing the consumers to receive price alerts from the utility [123]. Energy optimization requirements are:

- Power Requirements

This factor in wireless portable devices has always been one of the most important. The main motives for waste of energy embrace overhearing, idle listening, collision and control overhead. In last decade, significant developments were achieved in this area; however, an evolution towards more power-efficient elements must continue, especially for monitoring sensors, battery-powered devices, remote control and mobile handheld equipment, so as to extend the durability of these devices by saving as much energy as possible [124].

- Efficiency

The use of frequency spectrum can be costly so an effective result with the lowest amount of waste, unnecessary effort, or expense is desirable. With the aim of avoiding needless redundancy in the transmissions such outcome obliges an exhaustive reading of the power consumption data [50].

2.4. Wired HAN

Nowadays, there are many traditional and non-traditional transmission infrastructures such as telephone lines, electronic wiring, unshielded twisted pairs, coaxial cables, and optical fibers. A widely adopted power line communications technology named HomePlug uses the available home electricity wiring infrastructure to communicate, i.e., which is mainly used for high-speed wired communication applications (e.g., multi-stream entertainment networking) and has a developed set of standards [125].

Ethernet is a family of computer networking technologies for LANs and Metropolitan Area Networks (MANs). It is a common and widely adopted technology that offers a vast range of data rates (10Mbps – 1Gbps) or optical fibres (10Gbps) [126].

Ethernet technology uses a shared interface present in various parts of household equipment, such as printers, laptops, game consoles, servers, and Audio-Video (AV) equipment. Ethernet might not be the best option for connecting all the equipment and devices in the HAN (especially appliances) as a result of the power requirements and high cost, but perhaps the most important issue is with the need for separate wiring back to a central point. X10 is an international and open industry standard that utilizes power line cabling for signaling and control of home devices in which the signals include brief Radio Frequency (RF) bursts of digital information [127].

Yet, Ethernet suffers from some issues such as incompatibility with installed wiring and appliances, limited functionality, interference, excessive attenuation of signals between the two live conductors, slow speeds, lack of encryption, and frequent loss of commands [106]. Administered by the KNX Association, KNX is a standardized (EN 50090, EN 50090) OSI-based network communications protocol designed for smart buildings.

KNX is the improved replacement and enhanced version of three previous standards: BatiBUS, the European Home Systems Protocol (EHS) and the European Installation Bus (EIB or Instabus). All KNX installation devices are linked together by a dual wire bus — the most usual form of installation, consequently permitting them to exchange data [128].

The individual bus devices function is established by their project planning and can be adapted and modified at any time. KNX allows three bus topologies: line, star and tree, and can be mixed when needed, but it doesn't allow ring topologies. The tree topology has advantages over remaining ones in certain cases when a large network is required [129]. KNX contains a wireless Physical Layer (PHY) called KNX-RF and along with home automation networks, the basic PHY technology of KNX-RF is also utilized for the transmission of metering information between smart meters in Europe [130].

Other development by KNX Association is KNX IP — the name of the IP protocol when it is utilised as a pure KNX communication medium. Thus, KNX IP devices communicate with each other exclusively via KNX IP [131]. Several companies have been involved in development of a system that integrates powerline products with the already-established KNX system configuration. Thus, through powerline gateway it is possible for the system to receive and send information, events and commands to and from the electrical bus [132], [133].

Insteon defines a mesh topology composed of RF and power line links and it addresses X10 limitations while maintaining backward compatibility with X10. Insteon is a solution specifically developed for home automation and its devices can be power-line only or RF-only, or can support both forms of communication. All Insteon devices are peers, signifying that each device can transmit, receive, and repeat any message of the Insteon protocol, without requiring a routing software or master controller [106].

Local Operating Networks (LON, LonWorks) is a sensor/control networking technology that covers a wide range of applications. It has an architectural flexibility since its intelligent devices are projected to acquire data from the surroundings in a sensor network and also to interact with the sensed object in a feedback loop as a control network. LON is one of several solutions in building automation and home networking [134]. It comprises all the fundamental building automation subsystems: heating, air conditioning and ventilating, security, lighting, fire detection, energy monitoring and access control, fire valve control, gas detection, smoke detection. LON platforms are also utilized in semiconductor manufacturing, pulp and paper equipment, textile machinery, automotive, petrochemical, food and beverage, wastewater treatment, among others [135].

Most devices in LON-based building automation system are connected by wire, but wireless transmission is also used in cases like building-to-building communication, environmental monitoring of particular areas of the building or of stored materials in a building.

With LON platform, technology networked systems can be developed with a peer-to-peer architecture with a large number of nodes that exempts synchronization and generally cover wide distances. LON also utilizes multiple media including wireless communication, supporting battery-powered nodes, usually powered down and only activated for sending a message or receiving it [136]. All the previous described technologies support the IP protocol meaning that those can be easily integrated with IP-based smart grids. A global and non-profit trade group, The HomeGrid Forum, and its members are supporting and contributing to G.hn technology specification of the International Telecommunication Union's Telecommunication standardization sector (ITU-T) [125].

The main objective of G.hn technology is to merge the connectivity of media devices and digital content by providing a wired home network over coaxial, telephone, and data-grade cable networks, along with residential power line wiring in order to supply data at rates of up to 1Gb/s. *ITU G.hn* delivers secure connections between devices supporting IP and provides advantages, such as, self-installation by the consumer, the capability to connect to any room regardless of wiring type, self-management, built-in diagnostic information, and multiple equipment suppliers [116].

The Multimedia over Coax Alliance (MoCA) is an industry standard alliance developing technology for the connected home that runs over the existing in-home coaxial cabling that provides high quality performance and reliability for the home network. There are two versions of the specification currently available, MoCA 1.1 and MoCA 2.0 which are the deployed standards for the majority of service providers in North America.

It is also being adopted in other parts of the world. MoCA enables highly robust, low-latency, and secure communication at net throughputs of over 400/800 Mb/s and 1 packet error in 100 million Packet Error Rate. Its primary use is for the distribution of premium content high definition video and content, including applications such as multiroom digital video recorder [86].

The Meter-Bus (M-Bus) interface was developed for remote reading of household energy such as water or gas consumption meters and it can be also useful for security systems, heating or lighting control systems. M-Bus is an important communication technology for remote reading of meters in Europe, and standardized as EN13757-x [137].

M-Bus consists of a controller (master, MUC), a slave unit and a two-wire cable that are physically connected to each-other through twisted pair cables. The M-Bus interface has an exclusive feature that it can remotely supply counters with power, and the counters transmit the gathered data by demand of the master which in turn, the master connects to a mobile network modem or the Internet. To avoid loss of counter pulses in circumstances of power failure, M-Bus opts for power supply batteries as power replacement [101].

2.5. Wireless HAN

2.5.1. Based on IEEE Standards

The IEEE Standards comprise a family of networking standards that cover the Media Access Control (MAC) and PHY specifications for implementing wireless networks. IEEE 802.11 series standardize PHY and MAC layers for wide local area networks (WLAN) by employing frequency radio bands at 2.4 and 5.8 GHz. This range of standards and further evolutions offer the basis for wireless network products using the well-known Wi-Fi brand. Wi-Fi is a popular IP-based wireless technology used in home networks, mobile phones, video games, and other electronic devices. This set provides mobility, flexibility, and low-cost connection with the wired technology which makes it appropriate at the distribution level where the performance requirements and data rate are less strict and the cost of technology is more significant. Furthermore, advanced security and the QoS can in addition be reached using this technology [138].

The IEEE 802.15.4 is a standard for low-power, low data rate wireless communication between small devices. This standard only defines PHY and MAC layers, currently the most widely adopted standard for WSN in low power applications, low data rate (250kb/s at 2.4GHz), with lower complexity, and short range transmission [139].

Above IEEE 802.15.4 protocol, there are several standards like ZigBee, MiWi, 6LoWPAN, WirelessHART and ISA100.11a. In addition, these higher layer protocols define the suggested application framework, device profile, network layer, and security services among other functionalities. Bluetooth is designed for applications that are primarily based on computer peripherals, such as wireless keyboard and mouse [140].

Bluetooth or IEEE 802.15.1 is a standard intended to be a secured and cheap way of connecting and transferring data amongst supported devices, creating a PAN. At present, many versions of Bluetooth are available such as Bluetooth Low Energy (BLE), which is a short-range wireless transmission technology targeting low complexity, low-cost, communication in wireless BAN by utilizing frequency radio bands from 2.4 to 2.485 GHz [141]. Table 2.1 shows in detail the wireless networking protocols supported on IEEE Standards.

2.5.2. Not Based on IEEE Standards

There are several protocols that are not based on any kind of standardized PHY or MAC layers. These protocols are: Insteon, Z-Wave, SimpliciTI, EnOcean, among others. For comparison purposes, such protocols are shown in detail in Table 2.2.

- Insteon

It is a registered trademark for a home automation networking technology that enables light switches, lights, thermostats, motion sensors, and other devices to interoperate through power lines, radio frequency (RF) communications, or both [106].

- Z-Wave

Z-Wave networks has so far largely been used for home automation applications, e.g., controlling lights function, change the thermostat operation, controlling doors function, and control security systems (among other purposes). In addition, Z-Wave networks can handle up to 232 devices. Z-Wave radio frequency (RF) systems operate in the sub-Giga Hertz frequency range (≈900MHz) and at a nominal rate of 20kb/s [142].

Table 2.1. Wireless Network Based on IEEE Standards

Protocols / Specifications	ZigBee Over IEEE 802.15.4	WirelessHART Over IEEE 802.15.4	MiWi Over IEEE 802.15.4	Isa100.11Over IEEE 802.15.4	Bluetooth (IEEE 802.15.1)	Wi-Fi IEEE 802.11 a/b/g/n/ac/i
ISM Bands	2.4 GHz/915 MHz (USA)/868 MHz (EU)				2.4 GHz	2.4 GHz 5 GHz
Number of RF Channels	16 (2.4 GHz)/10 (915 MHz)/1 (868 MHz)				79 40 (v4.0)	14 (2.4 GHz) 8 (5 GHz)
Network Topology	Star, Peer-to-Peer and Mesh	Star, Peer-to-Peer and Mesh	Star, Peer-to-Peer	Star, Peer-to-Peer and Mesh	Star, Peer-to-Peer	Star, Peer-to-Peer
MAC Scheme	CSMA/CA TDMA + CSMA/CA (Star Topology)	TDMA + CSMA/CA (beacon mode)	CSMA/CA (beaconless mode)	TDMA + CSMA/CA (beacon mode)	TDD	CSMA/CA + PCF
Modulation Scheme	BPSK (868-915 MHz) Q-QPSK(2.4 GHz)	O-QPSK (2.4 GHz)	FSK/OOK	O-QPSK (2.4 GHz)	GFSK/DQPSK 8DPSK (optional)	BPSK, QPSK, COFDM, CCK, M-QAM
Nominal Rate	250 kbps (2.4 GHz) 40 kbps (915 MHz) 20 kbps (868 MHz)				1 Mbps (v1.2/v4.0) 3 Mbps (v2.0) 24 Mbps (v3.0)	11-65-450 (IEEE 802.11 n) Mbps
Power Saving Mechanism	Supported					
Encryption	AES128				AES64 and AES128	CCMP 128
Data Authentication	MIC-32; MIC-64;MIC-128 (Shared key) ENC-MIC-32;ENC-MIC-64;ENC-MIC-128 (Encrypted key)				Challenge response scheme	4-Way handshake
Data Integrity	CRC16	CRC16	CRC32	CRC16	CRC32	CRC32
Autonomy (Days)	100 to 1000+	Depends on Battery Specifications	Depends on Battery Specifications	Depends on Battery Specifications	1 to 10	0.5 to 5
Range (meters)	10-300	100	20-50	100-200	10	10-100
Application Areas	Demand Response, remote control and automation in residential and commercial buildings	Industrial Control, building control the sensory data conveying temperature, pressure or speed	AMR metering, consumer, electronics, home, automotive, industrial, automation, toys business and medical applications	Industrial and control market	Wireless connectivity between personal devices such as headphones, medical, mobile phones or laptops	Wireless LAN connectivity, broadband Internet access
Advantages	Low Power consumption, several application profiles (home automation, smart energy) and topology flexibility	Communication Security, reliability and Environment with wired HART infrastructure	Flexible, cost-effective platform	Low energy consumption devices, Robustness in the presence of infrastructure, flexible and communication security	Speed and flexibility	Speed and flexibility

- SimpliciTI

SimpliciTI is a simple open-source low-power RF network protocol developed by Texas Instruments Inc., and aimed at small RF networks. Typically contain battery operated devices which require long battery life, low data rate and low duty cycle and have a limited number of nodes talking directly to each other or through an access point or range extenders. Access point and range extenders are not required but provide extra functionality such as store and forward messages. With SimpliciTI, the MCU resource requirements are minimal which results in low system costs [143].

- EnOcean

This standard efficiently technology exploits applied slight mechanical excitation and other potentials from the surrounding environment (motion, pressure, light, and temperature) using the principles of energy harvesting for networking self-powered wireless sensors, actuators, and transmitters. In order to transform such energy fluctuations into usable electrical energy, electromagnetic, piezo-generators, solar cells, thermocouples, and other energy converters are used. The transmission range is around 30m from inside buildings, and this technology allows for wireless gateway connectivity with common automation systems [144].

- Wavenis

Developed by Coronis Systems is a wireless protocol stack for control and monitoring applications in several environments, involving both home and building automation. Wavenis is presently being endorsed and managed by the Wavenis Open Standard Alliance (Wavenis-OSA). It delineates the functionality of physical, link, and network layers. The access to Wavenis services can be made from superior layers through an Application Programming Interface (API). Wavenis runs mostly in the 433MHz, 868MHz, and 915MHz bands and some devices also operate in the 2.4GHz band. The maximum and minimum data rates presented by Wavenis are 100kb/s and 4.8kb/s, respectively, but 19.2kb/s is the most common value. Wavenis embraces Gaussian Frequency-Shift Keying (GFSK) modulation combined with Fast Frequency Hopping Spread Spectrum (FHSS) which is utilized over 50kHz bandwidth channels [106]. It delimits the operations at the PHY, data link and Network (NWK) layers, carried through proprietary APIs [145].

Table 2.2. Wireless Network Standards Not Based on IEEE Standards.

Protocols / Specifications	SimpliciTI	Z-Wave	Insteon	EnOcean	Wavenis	WM-Bus
ISM Bands	2.4 GHz and Sub 1 GHz	2.4 GHz 908.4 MHz (USA) 868.4 MHz (EU)	915 MHz (USA)	315 MHz (USA) 902.875 (USA) 868 MHz (EU)	433 MHz 868 MHz (EU) 915 MHz (USA) 2.4 GHz	169 MHz 433 MHz 868 MHz
Number of RF Channels	Set by the application	2	34	1	1	12
Network Topology	Star and peer-to-peer	Mesh	Dual-mesh (RF and powerline) Peer to peer and mesh	Star, peer-to-peer and mesh	Star, peer-to-peer and mesh	Star, peer-to-peer
MAC Scheme	LBT (Listen-before-talk)	CSMA/CA	CSMA/CA	CSMA/CA	CSMA/TDMA (synchronized networks) and CSMA/CA (otherwise)	CSMA/CA
Modulation Scheme	MSK	FSK, GSK, narrowband	BPSK, FSK (in ISM Band)	ASK	GFSK	FSK, GFSK, MSK, OOK,and ASK
Nominal Rate	Up to 250 kbps	9.6 kbps (868 MHz) 40 kbps (915 MHz)	38,4 kbps	120 kbps (868.3 MHz)	From 4.8 kbps to 100 kbps. Usually 19.2 kbps	2.4 kbps to 100 kbps
Power Saving Mechanism	Supported	Supported	Supported	Supported	Supported	Supported
Encryption	Depends on the radio MAC	AES128	No	No	3DES AES128	DES AES128
Data Authentication	Depends on the radio MAC	8-bit node I.D 32-bit home I.D	24 bit pre-assigned module I.D.	8/32-bit	48-bit MAC addresses	-
Data Integrity	Depends on the radio MAC	Assigned by primary controller	CRC16	CRC8	BCH (32,21)	CRC16
Autonomy (Days)	Depends on Battery Specifications	Depends on Battery Specifications	Depends on Battery Specifications	No batteries (is solar cells, electromagnetic)	Depends on Battery Specifications	Depends on Battery Specifications
Range (meters)	10	30	45 (outdoors)	30	200 (indoors) 1000 (outdoors)	Up to 1000
Application Areas	Distributed alarm and security devices, energy meters and home automation	Remote control lighting and automation, in residential and commercial buildings	Energy measurement, Energy savings, irrigation control, Occupancy sensing, Remote control heating and air conditioning	Building Automation, Smart Homes, Logistics, industry and transportation	Industrial Automation, AMI, AMR, Smart Homes, lighting and access control, cold-chain monitoring, active RFID applications	Smart Meters (Electricity, Gas, Water, and Heat)
Advantages	Small code size and low software complexity	Controllers and slaves network, flexible network configuration	Reliability, low cost, scalability and flexibility	Ultra-low Power, no batteries, Easy to install and time is saved	Ultra-low-power energy consumption, multiple years battery life	Very cost effective

- Wireless M-BUS

As continuation of the Metering Bus (M-Bus) standard for cable applications, the Wireless M-Bus (WM-Bus) has been developed, to properly operate with WSN scenarios, as partially done in some home automation context [146]. The absence of modularity is one of the main reasons why standardized routing protocols are not available for Wireless M-Bus at the present. The M-Bus benefits asymmetric network topologies with data collectors or gateways with higher performance on the one side and low-cost or low-power metering devices on the other side. Presently, it only supports star-network topologies or point-to-point topologies but it does not yet possible for mesh or multi-hop topologies [137].

The Wireless M-Bus (EN 13757-4:2005 and EN 13757-4:2011) has been lately recommended by the Open Metering System group 4 for metering scenarios and proposed for use in smart meters. The energy needs for WM-Bus transceivers are low due to a low-overhead protocol, transmission-only modes and long-range sub-GHz broadcast bands.

Furthermore, the first document EN 13757-4:2005 approved the use of the 468MHz ISM and 868MHz bands, the following standard version EN 13757-4:2011 added new extra communication modes at 169 MHz with reduced data rates [147].

The lower 169MHz frequency band allows higher transmission range thanks to the intrinsically lower path losses. In the meantime, lower data rates increase the receiver sensitivity, allowing a decrease of the transmission power at the transmitter or a longer transmission range for an identical transmission power [148]. The established WM-Bus modes are classified as following:

- T-form: 100kb/s data rate from meter to gateway, frequent transmission mode (several times per second or per minute), 868MHz. In T2 mode, the transmitter requires an acknowledgement (ACK) while T1 does not.
- S-form: 32.7kb/s, stationary mode (several transmissions per day), 868MHz. In S2 mode, the transmitter requires an ACK while S1 does not.

In both of the previous communication modes, the meter initiates the transmission to the concentrator, which in turn is always in reception mode. Once the transmission of the first packet is done, the sub-meter activates a reception window, waiting for the concentrator request or command.

The transmission session cannot be activated by the concentrator for the reason that the meters mostly remain in sleep mode in order to save the life of the battery, corresponding with what generally happens in low rate communication systems [149]. The WM-Bus protocol defines several specifications for the N mode, as follows [150]:

- Nc form: 2.4kb/s, 169.431MHz. N2c needs ACK, N1c does not.
- Na form: 4.8kb/s, 169.400MHz. N2a needs ACK, N1a does not.
- Ng form: 38.4kb/s, 169.437MHz. Ng always requires ACK.

The WM-Bus can reach longer distance transmissions when compared to IEEE 802.15.4. Sensor nodes equipped with ZigBee/802.15.4 transceivers can only cover a few dozens of meters. If greater distances are required to be covered employing ZigBee/802.15.4 technology, then a multi-hop data transfer strategy can be expected which, in exchange, raises the power requirements for the sensor nodes. WM-Bus not only allows long ranges, but it also offers a relaying method to cover longer distances with multi-hop techniques as defined in EN 13757-5 [146].

2.6. Wireless Networks Suitability to Functional Area Requirements

Smart home distributed applications have their own requisites in terms of bandwidth, auxiliary services such as secure data transmission, data authentication, and so on. A first criterion to consider is to trace data rate requirements as a function of the application as depicted in Figure 2.3. In addition, bandwidth needs between a minimum and a maximum can be consulted in Table 2.3 [58]. Home metering data transmissions along with energy management services show the lowest communication bandwidth. Due to its low data requirement, simple low power RF protocol can meet this specification from M-Bus to 802.15.4 based protocols. On the contrary, the number of applications that may be deployed for home health care solutions is, in terms of bandwidth, very wide [122]. Table 2.4, it is shown the cross of specific application requirements with the main attributes to characterise a HAN communication infrastructure. In one hand, the bandwidth necessities are clearly different being this, the first criterion of differentiation between functional areas [151].

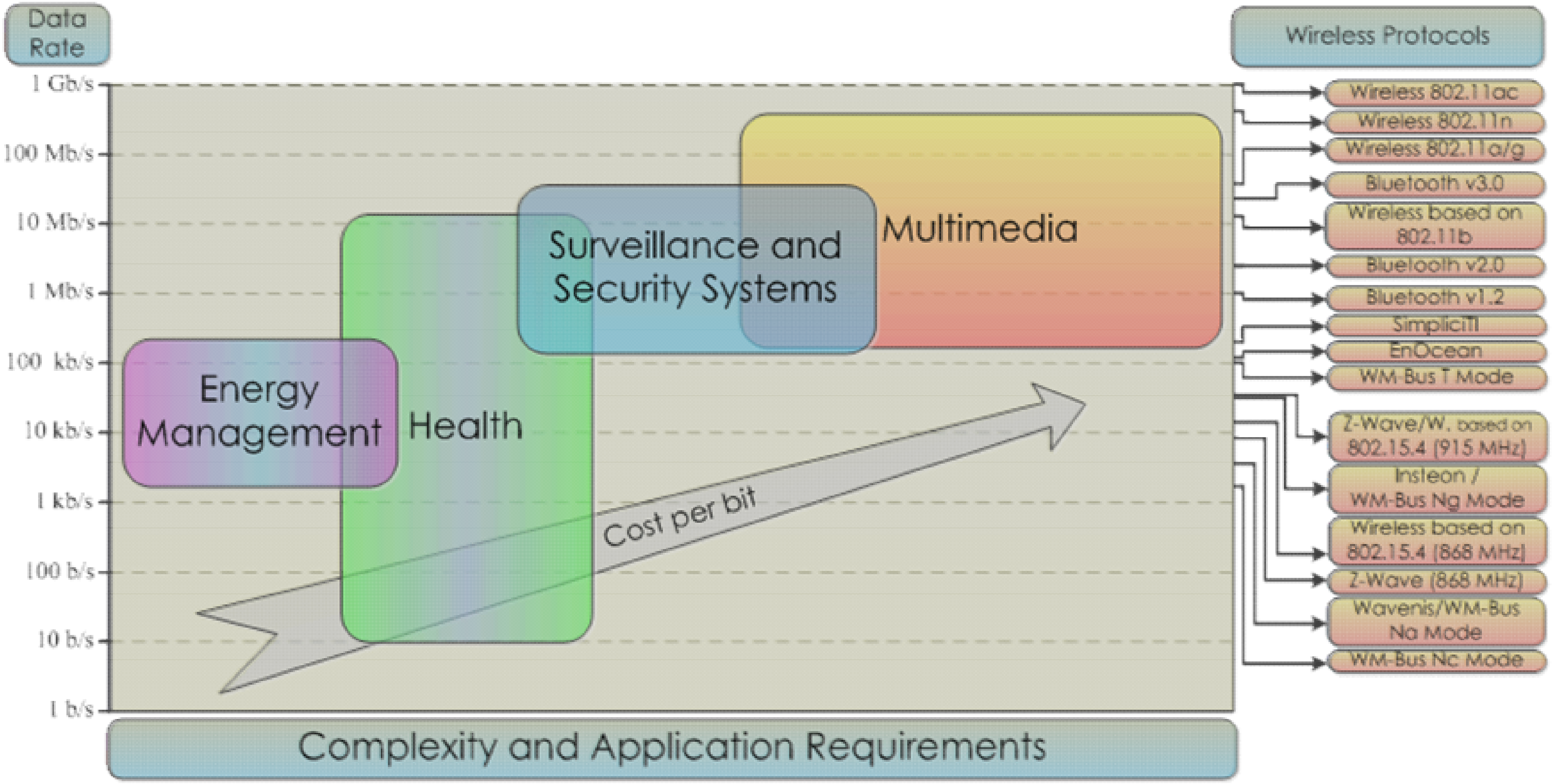


Figure 2.3. Wireless communication technologies for smart home application vs. data rate.

Notwithstanding, it has to be seen if HAN requirements comply with the home application necessities. From the set of analysed functional areas, the healthcare field seems to be the most demanding one, since the integration onto or into the human body of electronic devices for diagnostic, therapeutic, or surgical function have to comply with very restricted technical and biological requirements [152]. It is the only functional area that requires high portability medical devices that must be designed with a high-energy optimization concern in a way to maximize the lifetime of power supply (e.g., the battery).

In this case, the network must be prepared in such a way that if the condition of the network deteriorates, it would still be able to safeguard the minimum services of transmission [59]. Given that it dealt with sensible information on the patient health status, it was necessary to protect the transmission from data modification, impersonation, eavesdropping and replaying. The patients need to have a high autonomy, it must be assured that the *QoS* of transmission cannot be corrupted by electromagnetic interference or by transmission anomalies generated in the patient's radio [60]. Since the majority of multimedia devices are static and transmitted contents are not sensible, the security, dependability, network operation and energy optimization are low. When it comes to energy management, the load control has low risk; thus, it is not necessary for the communication infrastructure security to incorporate measures. Consequently, it means that, at this level, the protocol doesn't need to have advanced resources and bandwidth [153].

Likewise, for multimedia services, the majority of home appliances and devices are also static and the transmitted contents are not sensible; thus, the dependability, security, network operation and energy optimization are low as well, especially for services such as activation and deactivation of home appliances, HVAC control, illumination systems and real time energy consumption. For people and goods protection, the surveillance and security measures present different performance levels according to their objectives [154], [155]. However, for the aforementioned functional area, all of the implementations require network security and confidentiality measures, since it could mean a security brake with unpredicted consequences. In this context, the sensor networks integrated in the surveillance system have to be designed taking into account the energy optimization of their radio units.

Table 2.3. Data Rate specifications according to application area.

Functional Area		Application		Data Rate Requirements Minimum	Data Rate Requirements Maximum	Ref.
Energy Management	A	Activation and deactivation of home appliances/HVAC Control/Lighting System		2.4 kb/s	250 kb/s	[122], [156], [157], [158], [159], [160], [153], [161]
	A	Real time energy consumption				
	A	Smart Meters				
Health	B	Low Bandwidth (<250 kb/s)	Pulse Oximeter/Blood Pressure	12 b/s	15 Mb/s	[162], [151], [152]
	B	Medium Bandwidth (250 kb/s-1 Mb/s)	EMG/Deep Brain Simulation			
	B	High Bandwidth >1 Mb/s	Capsule Endoscopy			
Surveillance and Security Systems	C	Simple Alarms/Detections Sensors		200 kb/s	54 Mb/s	[156], [154], [155]
	C	CCTV Surveillance Camera				
	C	HD Video Surveillance				
Multimedia	D	Stereo Audio		250 kb/s	500 Mb/s	[86], [87], [163]
	D	Standard Definition TV (SDTV)				
	D	Whole Home distribution of HD Video and Content				

Table 2.4. Functional areas requirements vs. home area network (HAN) requirements.

HAN Requirements \ Functional Areas	A	A	A	B	B	B	C	C	C	D	D	D
Bandwidth	L	L	L	L	M	H	L	M	H	M	H	VH
Security	N	I	I	I	I	I	I	I	I	N	N	N
Dependability	N	N	I	I	I	I	N	I	I	N	N	N
Network Operation	N	N	I	I	I	I	N	N	N	N	N	N
Energy Optimization	N	N	N	I	I	I	I	N	N	N	N	N

L -Low; M -Medium; H -High; VH -Very High; N -Not Important; I -Important.

In order to match specific communication requirements with wireless architectures capabilities, a technical and economic trade-off is necessary to minimize the global implementation cost. In this regard, a set of critical features were identified and chosen to qualify wireless standard suitability [19], [82], [94], [155]. Table 2.5 clearly shows that the different services of a smart home have substantial differences in communication requirements. Therefore, none of the wireless protocols can be an answer to all the requisites. Generally, the analysed protocols can respond to the communication necessities and requirements in home energy management. However, there are exceptions where EnOcean and Insteon do not possess the necessary means to satisfy the requirements of a secure communication [106], [144].

Curiously, Z-Wave does possess requirements of a secure communication but does not have the minimum bandwidth to satisfy the necessities of networks that include smart meters or distributed power measurement units [142]. Given that SimpliciTI is a brand protocol, it is not clear if it activates the security functionalities in radio hardware. From an economic standpoint and since the bandwidth is low, it doesn't make sense to opt for Bluetooth units or Wi-Fi [155]. Besides, IEEE 802.11 is more power-hungry than, for instance, IEEE 802.15.4 in terms of the consumption of energy, that belongs to the low power class of networks.

Table 2.5. Functional Areas requirements vs. Wireless Protocols.

Functional Areas / Wireless Protocols	A	A	A	B	B	B	C	C	C	D	D	D
ZigBee Over IEEE 802.15.4	Y	Y	Y	Y	N	N	Y	N	N	N	N	N
MiWi Over IEEE 802.15.4	Y 1	Y 1	Y 1	Y 1	N	N	Y 1	N	N	N	N	N
Bluetooth (IEEE 802.15.1)	Y 2	Y 2	Y 2	Y	Y	Y	Y	N	N	Y	Y	N
Z-Wave	Y	N	N	Y 5	N	N	Y	N	N	N	N	N
Wi-Fi IEEE 802.11	Y 2	Y 2	Y 2	Y 2	Y 2	Y 2	Y 2	Y 2	Y 2	Y	Y	Y 6
EnOcean	Y	N	N	N	N	N	N	N	N	N	N	N
Insteon	Y	N	N	N	N	N	N	N	N	N	N	N
SimpliciTI	Y	N	N	Y	N	N	N	N	N	N	N	N
Wavenis	Y	Y 4	Y 4	Y 4	N	N	Y	N	N	N	N	N
WM-Bus	Y	Y 4	Y 4	Y 4	N	N	Y	N	N	N	N	N
Isa100.11 Over IEEE 802.15.4	Y	Y 1	Y 1	N	N	N	Y	N	N	N	N	N
WirelessHART Over IEEE 802.15.4	Y	Y 1	Y 1	N	N	N	Y	N	N	N	N	N

1—Only 2.4 GHz; 2—Minimum requirements over-exceeded; 3—Up to 120 kbps; 4—Up to 100 kbps; 5—Up to 40 kbps; 6—Not Recommended see [93] Y -yes complies N -not complies.

Contrary to the energy management of the smart home, the healthcare appliances require a far superior bandwidth and are exigent for high security levels of transmission and reception. With the exception of Bluetooth and Wi-Fi, the remaining networks can only satisfy the requirements of low bandwidth application. Insteon and EnOcean do not follow the minimum requirements of network security [106], [144]. For support services of home surveillance and the introduction of HD video, the bandwidth necessities rise significantly, thus, putting Wi-Fi as the only candidate to fulfill those requirements.

Due to the limited range and comparatively lower data rate than Wi-Fi, Bluetooth is not a choice for this functional area [141]. Finally, the class of applications dedicated to advanced multimedia is by nature very demanding on the data rate without necessarily requiring network security measures. Therefore, Wi-Fi at least for *n* version could support HD video transmission while the same implementation in Bluetooth can only support video in the conventional format.

Although 802.11n could, in theory, fit for the most exigent multimedia service, a new protocol called Wireless Gigabit Alliance (WiGiG) wireless communications in the 60GHz band has been developed specifically for this purpose [163]. Despite Isa100.11 and WirelessHART being designed for the industry sector, they were selected merely as a comparison factor, but these networks can also fit for several home automation tasks, alarms, switches, smoke detectors, energy management of appliances such as heater and cooler, oven among others. Insteon and EnOcean have serious limitations in terms of guaranteeing a minimally secure communication; besides, they have a low data rate [106], [144].

The remaining low power data rate networks, when eligible, present similar technical specifications; thus, the selection has to undergo an analysis of development, installation and operational cost. Consequently, it is necessary to analyse which are the implementation memory, CPU requirements, and the wireless protocol, and analyse the energy profile according to data traffic. From a market standpoint, several wired and wireless protocols analysed in this study are competing for use in medical applications. Although all of the analysed protocols have real and tangible benefits such as lower cost, less protocol complexity and overheads, and less traffic to contend with, Wi-Fi is a best choice with better position to capture the wearable medical device market for a number of reasons briefly described before [154].

The most important reason is that Wi-Fi is widely deployed compared to other protocols. Malls, hotels, restaurants, and other public places are being equipped with free Wi-Fi, which are making them an ideal channel for medical devices that need to communicate directly to the cloud and a medical professional through the public infrastructure. Nevertheless, the technical limitations resulting from this choice will have to be overcome by strengthening the planning of the network with very careful implementation, which includes adopting extra-level functionalities at the protocol application layer level [164].

Chapter 3

Smart Household Operation

Smart household operation considers bi-directional electric vehicle and energy storage system utilization by real-time pricing-based demand response. As a new type of consumer load in the electric power system, EVs also provide different opportunities, including the capability of utilizing EVs as a storage unit via Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) options instead of peak power procurement from the grid. In this study, the main contribution is a collaborative evaluation of dynamic-pricing and peak power limiting-based Demand Response (DR) strategies with a bi-directional utilization possibility for EV and Energy Storage System (ESS). A Mixed-Integer Linear Programming (MILP) framework-based modeling of a Home Energy Management (HEM) structure is provided for this purpose. A distributed small-scale renewable energy generation system, the V2H and V2G capabilities of an EV, together with two-way energy trading of ESS, and different DR strategies are all combined in a single HEM system. The impacts of different EV owner consumer preferences together with the availability of ESS and two-way energy trading capabilities on the reduction of total electricity prices are examined with case studies.

3.1. Introduction

There are several recent studies dealing with DR strategies for the optimum appliance operation of smart households. Chen *et al.* [165] and Tsui *et al.* [166] developed an optimization strategy for the effective operation of a household with a price signal-based DR [165]. Li *et al.* [167] proposed a "user-expected price" — based DR strategy for a smart household, including also a battery-based ESS aiming at lowering the total electricity cost by charging and discharging the ESS at off-peak and peak price periods, respectively.

However, the impact of including an additional EV load that can also be helpful for peak clipping in certain periods when EV is at home and the possibility of an own production facility have not been evaluated.

Zhao *et al.* [168] considered the HEM strategy-based control of a smart household including PV-based own production facility and availability of EV and ESS. However, V2H and further possible V2G operating modes of EV have not been taken into account. Restegar *et al.* [169] developed a smart home load commitment strategy considering all the possible operating modes of EV and ESS. However, that study neglected the impact of an extra peak power limiting strategy that is probable to be imposed by a load serving entity (LSE). Pipattanasomporn *et al.* [170] and Kuzlu *et al.* [171] presented a HEM strategy considering peak power limiting DR strategy for a smart household, including both smart appliances and EV charging. Shao *et al.* [172] also investigated EV for DR-based load shaping of a distribution transformer serving a neighborhood. References [170] - [172], did not provide an optimum operating strategy considering price variability with the aim of obtaining the lowest daily cost apart from just limiting the peak power drawn from the grid by the household in certain periods.

Matallanas *et al.* [173] applied an HEM system based on neural networks with experimental results for a household including PV and ESS. However, the impacts of varying price as well as other types of DR strategies have not been evaluated. De Angelis *et al.* [174] performed the evaluation of a HEM strategy considering the electrical and thermal constraints imposed by the overall power balance and consumer preferences. Chen *et al.* [175] provided an appliance scheduling in a smart home considering dynamic prices and appliance usage patterns of consumer. Missaoui *et al.* [176] also provided a smart building energy management strategy based on price variations and external conditions as well as comfort requirements. The pricing data-based energy management has also been suggested by [66] together with a hardware demonstration. Erdinc [177], considered both pricing and peak power limiting DR, but neglected the possibility of two-way energy trading possibility for EV and ESS with the grid, which can further improve the economic advantage of the HEM structure by increased flexibility.

These works together with many other studies not referred here have provided valuable contributions to the application of smart grid concepts in household areas. However, many of the mentioned studies failed to address distributed renewable energy contribution to reduce load demand on utility side, V2H option of EV to lower the demand peak periods, and two-way energy trading capability of EV (with V2G) and a possible ESS together with different DR strategies.

To our best knowledge, this is the first study in the literature combining all of the aforementioned operational possibilities in a single HEM system formulated in a MILP framework, which is the main novelty of this study. Different case studies are conducted considering the impacts of having a HEM system, an EV capable of providing V2H and V2G options, and an additional ESS under different DR strategies. The impacts of all case studies in terms of consumer electricity bill reduction performance are evaluated with relevant comparisons. Besides, real-time measured load demand and normalized PV-based distributed energy resource production data are utilized.

3.2. Methodology

The block diagram of a fundamental DR strategy is presented in Figure 3.1. The HEM system regulates the operation of the smart household considering price-based and other signals from the LSE, production of small-scale own facilities, load consumption of smart appliances, etc., together with different consumer preferences.

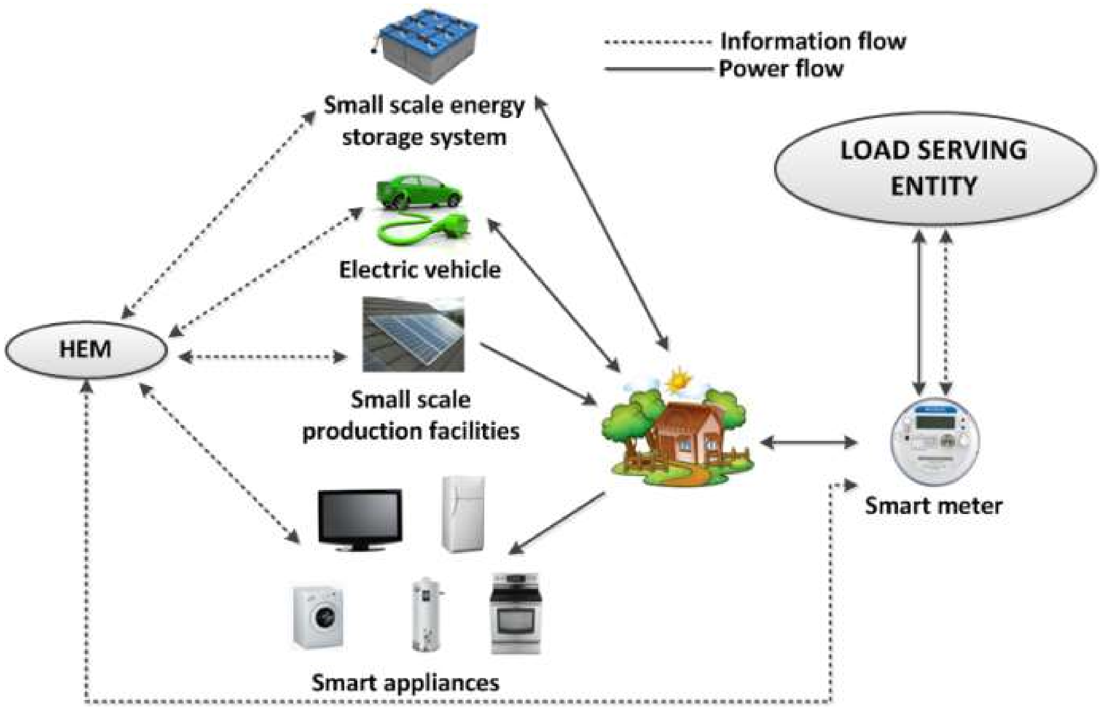


Figure 3.1. Block diagram of a fundamental DR strategy for smart households.

The objective is to minimize the total daily cost of electricity consumption. The cost is the difference between the energy bought from the grid and the energy sold back to the grid by the household-owned assets that are able to provide energy (PV, ESS, and EV). The price variables are time dependent, a fact that implies time varying prices for both bought and sold energy.

The second part of the objective function in (3.1) imposes an artificial penalty to the energy provided by the different resources. The ε parameters have sufficiently small positive values (such as e^{-7}, $2e^{-7}$, and $3e^{-7}$) that are determined by assumptions, so that the total cost is not affected. This technique serves the need of having a priority in selling energy from the resources. From the last observations, smaller relative value of a specific ε forces the HEM system to sell first all the energy available from that resource before selling energy from another. This can be described:

$$Minimize\ TC = \sum_t \left(\frac{P_t^{grid}}{\Delta T} \cdot \lambda_t^{buy} - \frac{P_t^{sold}}{\Delta T} \cdot \lambda_t^{sell} \right) + \sum_t \left(\varepsilon_1 \frac{P_t^{PV,\ sold}}{\Delta T} + \varepsilon_2 \frac{P_t^{ESS,\ sold}}{\Delta T} + \varepsilon_3 \frac{P_t^{EV,\ sold}}{\Delta T} \right) \tag{3.1}$$

Equation (3.1), the optimization variables are the total power bought from the grid at time t (P_t^{grid}), and the total power sold back to the grid (P_t^{sold}) which comprises power values sold from PV, ESS, and EV ($P_t^{PV,sold}$, $P_t^{ESS,sold}$, and $P_t^{EV,sold}$). In this study, we consider that the HEM system first sells energy from the PV, next from the ESS, and finally from the EV battery, which means $\varepsilon_1 < \varepsilon_2 < \varepsilon_3$. The constraints presented hereafter comprise the basic body of the HEM system operation.

The model can be easily extended and adapted to other more specific implementations (e.g., by further modelling specific smart-appliances such as HVAC, water heaters, appliances with cycling operation and/or customer's contract details). Any time granularity can be used simply by selecting the appropriate T. For instance, for a 15-min interval the T coefficient must be 4, as 1h comprises four 15-min intervals.

3.2.1. Power Balance

Equation (3.2) states that the load consisting of the residential load (P_t^{other}), the charging needs of the EV ($P_t^{EV,ch}$), and the ESS ($P_t^{ESS,ch}$) is either satisfied by the grid (P_t^{grid}) or by the combined procurement of energy by the PV, the EV, and the ESS ($P_t^{PV,used}$, $P_t^{EV,used}$, $P_t^{ESS,used}$). Mathematically, the power balance is described:

$$P_t^{grid} + P_t^{PV,used} + P_t^{EV,used} + P_t^{ESS,used} = P_t^{other} + P_t^{EV,ch} + P_t^{ESS,ch}, \;\; \forall t. \quad (3.2)$$

3.2.2. ESS Modeling

Equation (3.3) enforces the fact that the actual power provided by the ESS discharge ($P_t^{ESS,\mathrm{dis}} \cdot DE_{ESS}$) can be used to cover a portion of the household needs ($P_t^{ESS,\mathrm{used}}$) or injected back to the grid ($P_t^{ESS,sold}$). Constraints (3.4) and (3.5) impose a limit on the charging ($P_t^{ESS,\mathrm{ch}}$) and discharging ($P_t^{ESS,\mathrm{dis}}$) power of the ESS. The idle ESS state can be described by any of these constraints by the time the respective power variable is allowed to have zero value. Equations (3.6)-(3.9) describe the state-of-energy of the ESS. Constraint (3.6) forces the state-of-energy at every interval (SOE_t^{ESS}) to have the value that it had at the previous interval (SOE_{t-1}^{ESS}) plus the actual amount of energy that is transferred to the battery if it is charging at that interval minus the energy that is subtracted if the battery is discharging during that interval.

$$P_t^{ESS,\mathrm{used}} + P_t^{ESS,\ sold} = P_t^{ESS,\ dis} \cdot DE_{ESS}, \quad \forall t \quad (3.3)$$

$$P_t^{ESS,ch} \leq CR_{ESS} \cdot u_t^{ESS}, \qquad \forall t \quad (3.4)$$

$$P_t^{ESS,dis} \leq DR_{ESS} \cdot (1 - u_t^{ESS}), \qquad \forall t \quad (3.5)$$

$$SOE_t^{ESS} = SOE_{t-1}^{ESS} + CR_{ESS} \cdot \frac{P_t^{ESS,ch}}{\Delta T} - \frac{P_t^{ESS,dis}}{\Delta T}, \qquad \forall t \geq 1 \quad (3.6)$$

$$SOE_t^{ESS} = SOE^{ESS,ini}, \quad if\ t = 1 \tag{3.7}$$

$$SOE_t^{ESS} = SOE^{ESS,max}, \ \ \forall t \tag{3.8}$$

$$SOE_t^{ESS} = SOE^{ESS,min}, \ \ \forall t \tag{3.9}$$

At the beginning of the time horizon the state of-energy of the ESS coincides with the initial state-of-energy of the ESS ($SOE^{ESS,ini}$), as described in Equation (3.7). Equation (3.8) limits the state-of-energy of the battery to be less than the ESS capacity ($SOE^{ESS,max}$). Similarly, Equation (3.9) prevents the deep discharge of the battery by imposing a least state-of-energy limit ($SOE^{ESS,min}$).

3.2.3. EV Modeling

Equation (3.10) enforces the fact that the actual power provided by the EV discharge ($P_t^{EV,dis} \cdot DE_{EV}$) can be used to cover a portion of the household needs ($P_t^{EV,used}$) or injected back to the grid ($P_t^{EV,sold}$). Equation (3.11) and Equation (3.12) impose a limit on the charging ($P_t^{EV,ch}$) and discharging ($P_t^{EV,dis}$) power of the EV. The idle EV state can be described by any of these constraints by the time the respective power variable is allowed to have zero value. Equations (3.13)-(3.17) describe the state-of-energy of EV.

Equation (3.13) forces the state-of-energy at every interval (SOE_t^{EV}) to have the value that it had at the previous interval (SOE_{t-1}^{EV}) plus the actual amount of energy that is transferred to the EV battery if it is charging at that interval minus the energy that is subtracted if the EV battery is discharging during that interval.

At the arrival time of EV to household, the state-of-energy of the EV coincides with the initial state-of-energy of the EV ($SOE^{EV,ini}$), as described by Equation (3.14). Equation (3.15) limits the state-of-energy of the EV battery to be less than its capacity ($SOE^{EV,max}$). Similarly, Equation (3.16) prevents the deep discharge of the EV battery by imposing a least state-of-energy limit ($SOE^{EV,min}$). Equations (3.17) and (3.18) represent the option of having the EV battery fully charged or discharged at the least state-of-energy at pre-selected time intervals.

Finally, Equation (3.19) ensures that all the variables related to EV modeling are zero apart from the time interval between arrival time of EV to household (T^a) and departure time of EV from household (T^d).

$$P_t^{EV,used} + P_t^{EV,sold} = P_t^{EV,dis} \cdot DE_{EV}, \forall t \in [T^a, T^d] \tag{3.10}$$

$$P_t^{EV,ch} \leq CR_{EV} \cdot u_t^{EV}, \qquad \forall t \in [T^a, T^d] \tag{3.11}$$

$$P_t^{EV,dis} \leq DR_{EV} \cdot (1 - u_t^{EV}), \qquad \forall t \in [T^a, T^d] \tag{3.12}$$

$$SOE_t^{EV} = SOE_{t-1}^{EV} + CE_{EV} \cdot \frac{P_t^{EV,ch}}{\Delta T} - \frac{P_t^{EV,dis}}{\Delta T}, \quad \forall t \in [T^a, T^d] \tag{3.13}$$

$$SOE_t^{EV} = SOE^{EV,ini}, \qquad if\ t = T^a \tag{3.14}$$

$$SOE_t^{EV} \leq SOE^{EV,max}, \quad \forall t \in [T^a, T^d] \tag{3.15}$$

$$SOE_t^{EV} \geq SOE^{EV,min}, \quad \forall t \in [T^a, T^d] \tag{3.16}$$

$$SOE_t^{EV} = SOE^{EV,max}, \qquad \forall\ t \geq T^{f,c} \in [T^a, T^d] \tag{3.17}$$

$$SOE_t^{EV} = SOE^{EV,min}, \qquad if\ t = T^{f,d} \in [T^a, T^d] \tag{3.18}$$

$$SOE_t^{EV} = P_t^{EV,used} = P_t^{EV,sold} = P_t^{EV,dis} = P_t^{EV,ch} = 0 \quad \forall t \notin [T^a, T^d] \tag{3.19}$$

3.2.4. PV Modeling

Similarly to Equations (3.3) and (3.10), Equation (3.20) enforces the fact that the actual power provided by the PV ($P_t^{PV,pro}$) can be used to cover a portion of the household needs ($P_t^{PV,used}$) or injected back to the grid ($P_t^{PV,sold}$).

$$P_t^{PV,used} + P_t^{PV,sold} = P_t^{PV,pro}, \qquad \forall t \tag{3.20}$$

3.2.5. Total Power Injected to the Grid

The total amount of power injected to the grid (P_t^{sold}) consists of the amount of power provided by the PV ($P_t^{PV,sold}$), the ESS ($P_t^{ESS,sold}$) and the EV ($P_t^{EV,sold}$) as mentioned before. This is enforced by Equation (3.21).

$$P_t^{sold} = P_t^{PV,sold} + P_t^{ESS,sold} + P_t^{EV,sold}, \quad \forall t \tag{3.21}$$

3.2.6. Power Transaction Restrictions

Equations (3.22) and (3.23) implement the logic of power exchange. If power from the grid is needed to be drawn, then it is not possible to inject power back to the grid. The reverse case is also described by these constraints. N_1 is a positive integer value that imposes a limitation on the power that can be drawn from the grid. This limitation may represent a restriction posed by the aggregator or the responsible entity for the end-user electrification in order to face the situation where in its control area exist multiple households that own HEM system. The implementation of a time-varying peak power drawn from the grid limit as a different DR strategy can be easily adapted on this formulation, by replacing the N_1 by a time-dependent parameter.

$$P_t^{grid} \leq N_1 \cdot u_t^{grid}, \quad \forall t \tag{3.22}$$

$$P_t^{sold} \leq N_2 \cdot \left(1 - u_t^{grid}\right), \quad \forall t \tag{3.23}$$

Similarly, N_2 imposes a limit on the power that can be injected back to the grid and also can be replaced by a time-dependent parameter. Different consumer options and behavioral details can be expressed by fixing the charging and discharging variables of the ESS and EV to be zero in the appropriate time intervals. Different policies (e.g. energy selling back options) can be modeled by fixing the selling energy/power variables to zero or other desired values.

3.3. Test and Results

To evaluate the total impact of different case studies in household operation on consumer electricity bills, the MILP model is tested in GAMS v.24.1.3 using the solver CPLEX v.12 [178] and the relevant obtained results are discussed in this section.

The real-time measured load demand of an average house in Portugal is used in this study. The nearly 140 meter-square household includes 4 habitants with different electric appliances, including fridge, TVs, microwave, washing machine and dishwasher, computer, oven, etc. It should be noted that the household includes a water heater using gas instead of electricity.

The consumption of each day in a period of one month was recorded and the obtained average power consumption profile of this period is shown in Figure 3.2. It is considered in this study that the household includes a small-scale PV system of 1 kW. The production data of the mentioned PV system is the normalized version of a measured daily solar farm production profile. The considered PV system power production curve is given in Figure 3.3.

A bi-directional EV operation including both V2G (meaning that EV sells energy back to the grid) and V2H (meaning that a portion of the energy stored in EV battery is used to partly cover the household load) options is considered. The specifications of a Chevy Volt with a battery rating of 16 kWh is taken into account. The Chevy Volt is employed with a charging station limited to a charging power of 3.3 kW [27]. The same power limit is also assumed to be valid for the discharging operation in V2G and V2H modes. The charging and discharging efficiencies are considered 0.95.

It is also considered that the initial EV battery energy is 8 kWh (50% state-of-energy) while arriving at home and the lower limit of EV state-of-energy is restricted to 4.8 kWh (30% state-of-energy) to avoid deep-discharging (a limit around the level proposed by [179], announcing that the battery users should not extract more than 70-80% of the available capacity at any time). The following assumptions hold for the ESS; it consists of a battery group of 1kWh capacity. The charging and discharging rate per hour is assumed to be 0.2kW.

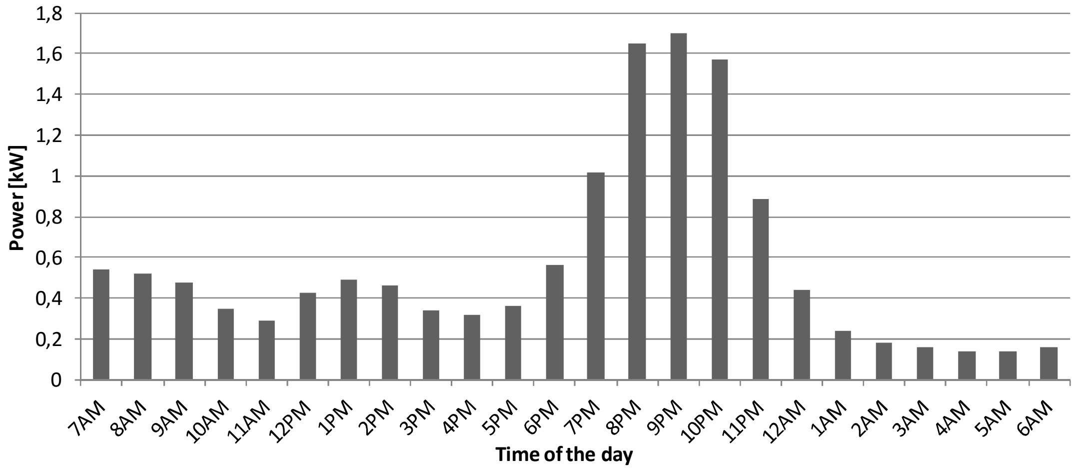


Figure 3.2. The real-time measured average household power demand.

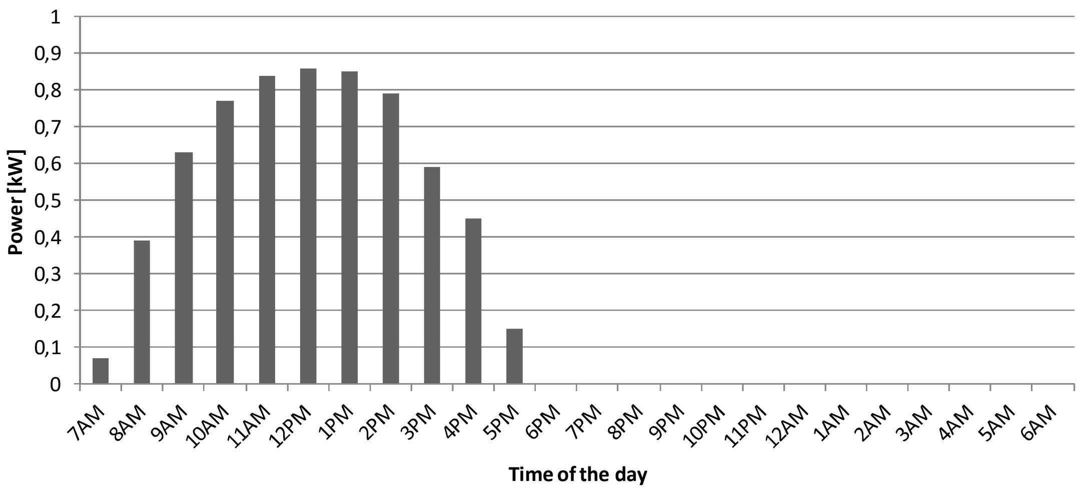


Figure 3.3. PV system power production curve.

From the previous point, its initial state-of-energy and charging/discharging efficiencies are 0.5kWh and 0.95kWh, respectively, and its deep-discharging limit is 0.25kWh. It should be noted that in the considered concept, no cost is associated with using storage facilities such as EV and ESS during the HEM operation. Integrating the two-way energy transactions between the end-user and the utility, the net-metering approach is utilized. When the available energy from the household-owned resources is sufficient to cover the total of the needs, the excess of energy can be sold back to the grid and vice versa. For pricing the bought energy from the grid, a dynamic pricing based DR scheme is considered.

The time-varying price signal available for the consumer via the smart meter is shown in Figure 3.4 [166]. Besides, a flat rate of 3 cents/kWh is paid to the end-user for the energy sold-back to the grid. Payment of flat rates with net metering is an approach also used in practice such as the case in Turkey. A dynamically changing rate for energy sold can also be easily applied within the provided formulation, as Equation (3.1) is suitable both for considering flat and dynamic rates. DR strategies, especially price-based DR activities are mainly considering the preferences of the consumer, and the preferences of the consumers may vary individually. Thus, first of all, sole consumer preferences based manual operation without HEM strategy is analyzed in this study.

Three types of consumer preferences, namely consumers willing to charge their EV immediately, consumers willing to charge their EV with lower prices, and consumers willing to charge their EV with lower prices together with utilization of EV V2H option for peak household power demand periods, are evaluated. Figure 3.5 presents the total household power demand for consumers willing to charge their EV immediately after arriving home at 6:00pm. It can be clearly seen that the EV load contributes significantly to the available peak period in the load demand given in Figure 3.2, and this peak reaches nearly 5kW instead of the available peak power value of 1.7kW in the household power demand. Here, the prices where the EV charging significantly contributes to the peak load are at the highest level compared to the other periods of the day: 4 cents/kWh at 6:00pm and 4.5 cents/kWh at 7:00pm. This issue surely has an impact on the total daily cost of household power demand supply.

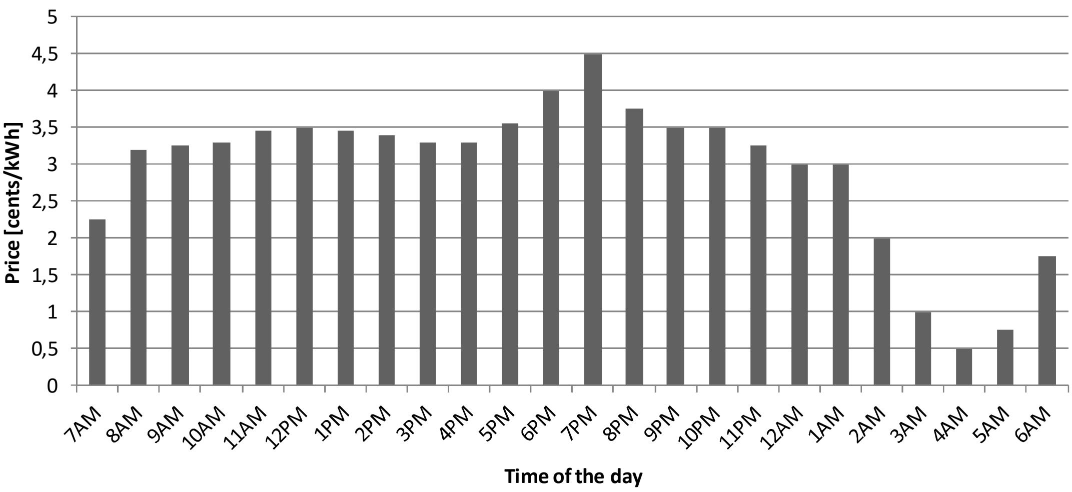


Figure 3.4. Time-varying dynamic price signal for DR.

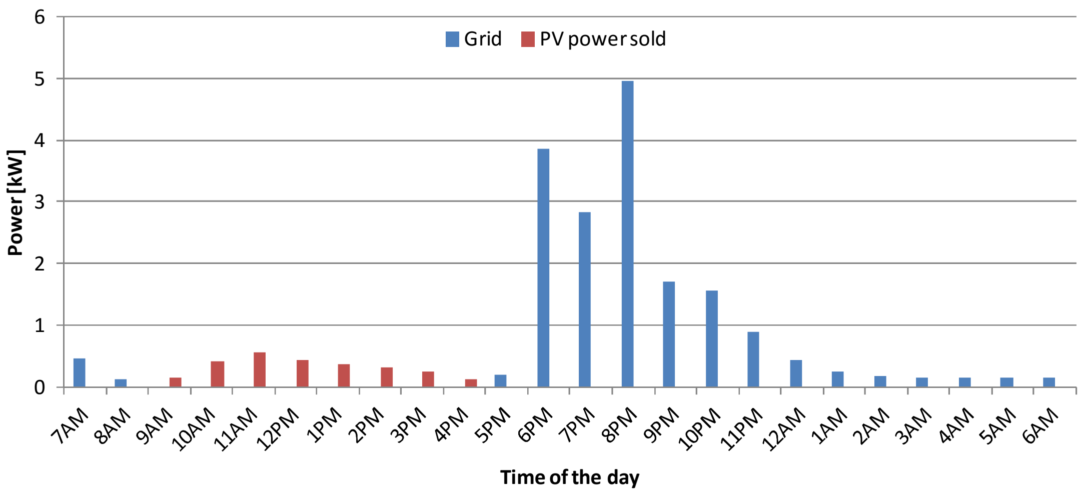


Figure 3.5. Total household power demand for consumers willing to charge their EV immediately.

The second preference of the consumer for charging EV with lower prices within the period starting from 10:00pm provides the total household power demand profile shown in Figure 3.6. This type of operation leads to 51.7 cents daily electricity consumption cost.

It should be noted that the reason for presenting these monetary values for this case and the cases that will be discussed below is to better present the impact of different preferences and the proposed methodology on the cost reduction for the daily operation of a household. These monetary values were not just given as numbers; instead, they will further be used to give percentages for the cost reduction for each case compared to a base case. To be able to provide a comparative analysis in order to present the merits of the proposed methodology, such percentages will be necessary. Shifting further the EV charge to even more low-price periods after midnight starting from 2:00am is also considered as a different case.

This leads to a significantly lower total cost of 33.3 cents. However, this issue has a serious disadvantage of providing new peaks in normally off-peak periods of utility load as seen in Figure 3.7 and requires a further power limiting action like in References. [167], [168], [169]. As a further case study, the consumer's will to charge the EV with lower prices together with an EV V2H option to decrease the energy procurement from the grid during peak price periods is examined.

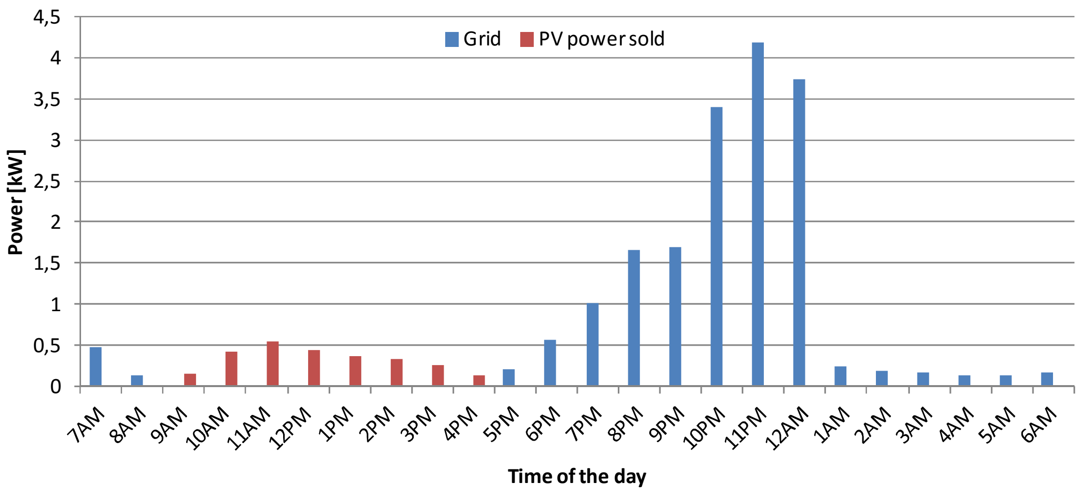


Figure 3.6. Total household power demand for consumers willing to charge their EV with lower prices (within the period starting from 10:00 pm).

The total household power demand profile is shown in Figure 3.8. It is considered in this case study that as soon as the EV owner arrives home at 6:00pm, the EV is plugged-in and the household power demand is supplied by the EV until the battery energy reaches the lower battery energy limit. After reaching this limit, procurement of energy from the grid starts again. Besides, the EV is charged during lower price periods. The total daily consumption cost is 49.6 cents if the EV is charged within the period starting from 10:00pm. The EV battery state-of-energy variation in this period is presented in Figure 3.9. As can be seen, the stored energy level of the EV battery reduces while connected to the household in V2G mode to the pre-defined lower limit of discharge and the EV battery remains idle after this period until the charging process within the period starting from 10:00pm.

Then, the EV battery is charged with the maximum allowed charging power until it is fully charged for the day-ahead utilization of the consumer. It should be noted here for Figure 3.8 and Figure 3.9 (and for all other figures) that the hour written below the figure corresponds to the time interval between the written hour and the next hour. For example, 6:00pm (the time EV arrives home) corresponds to the time interval from 6:00pm to 7:00pm in Figure 3.9. This is why the state-of-energy value is less than the initial state-of-energy value of EV battery at 6:00pm in Figure 3.9 as 6:00pm also includes the utilized energy from EV till 7:00pm.

If further lower price periods after midnight starting from 2:00pm are considered for the EV charging with V2H option in this case study, the cost decreases to 23.6 cents. This is the result of the combined impact of V2H option in peak periods and EV charging in lower price periods. Since now, manual DR activities have been analyzed in terms of the impact of different consumer preferences on daily electricity cost.

However, as the main advantages of a smart household are considered to be clearer with the implementation of an automatic HEM system, the impacts of employing such a system on costs for different options is also evaluated in this study. The HEM system considers the daily electricity prices declared by the entity that serves the load, together with regular load demand patterns of the household to decide the optimum operating strategy.

Firstly, the EV charging by optimization based HEM strategy without V2H option is evaluated. The HEM based EV charging strategy results in the total household power demand shown in Figure 3.10. As seen in, the HEM strategy automatically shifts the EV charging after 2:00am and especially after 4:00am, and the EV charging power is at its highest level due to the lowest electricity prices throughout the day. This type of operation leads to a total daily electricity cost of 30.5 cents that is considerably lower than the case where consumers manually decide the charging time of their EVs without V2H option.

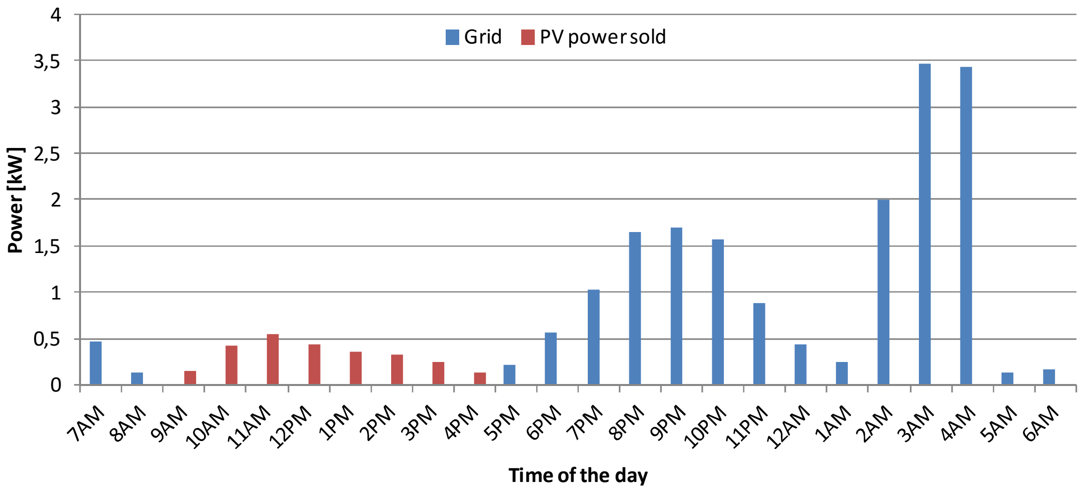


Figure 3.7. Total household power demand for consumers willing to charge their EV with lower prices (within the period starting from 2:00am).

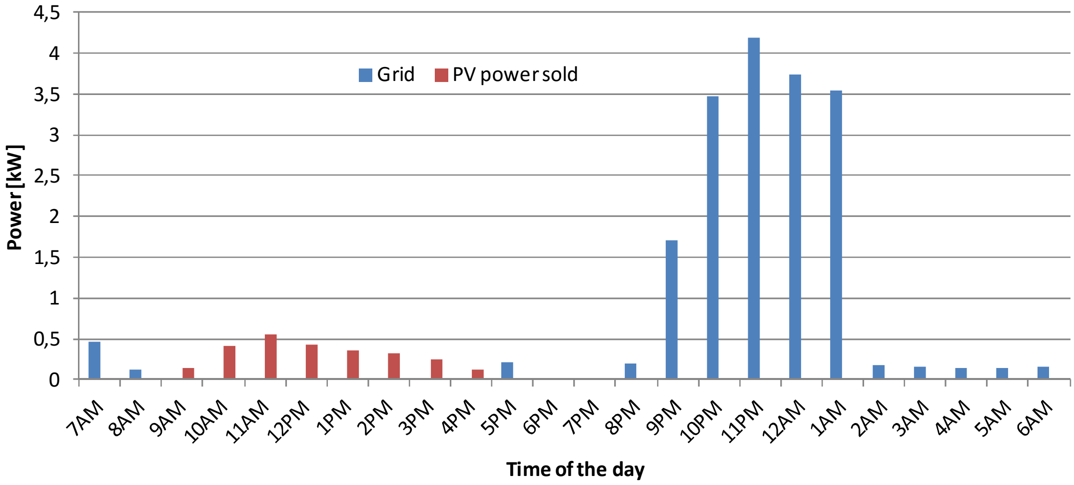


Figure 3.8. The total household power demand for consumers willing to charge their EV with lower prices together with EV V2H option (within the period starting from 10 pm).

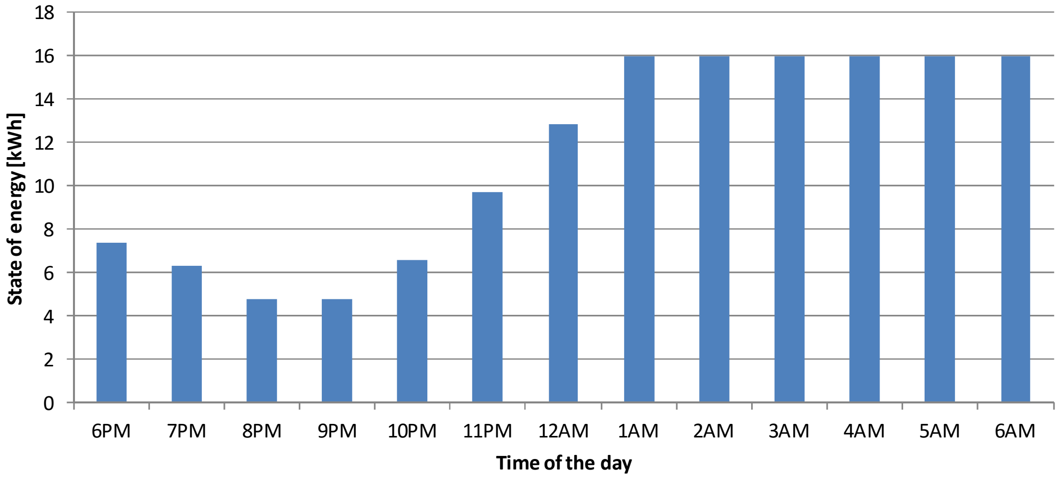


Figure 3.9. EV battery state-of-energy variation for consumers willing to charge their EV with lower prices together with EV V2H option (within the period starting from 10 pm).

As a further case study, the HEM based EV operation with the V2H option is examined. The beginning of EV charging is automatically shifted to 3:00am as can be seen in Figure 3.11, similarly to the previous case study where the HEM based EV operation is evaluated without V2H option. The state-of-energy variation of EV battery is shown in Figure 3.12. The EV battery stored energy level reduces until it reaches 30%, remaining at this level while EV is in idle mode and reaches 100% after charging, respectively, throughout the daily operation. This HEM based operation with additional V2H option leads to a total daily cost of 21.9 cents.

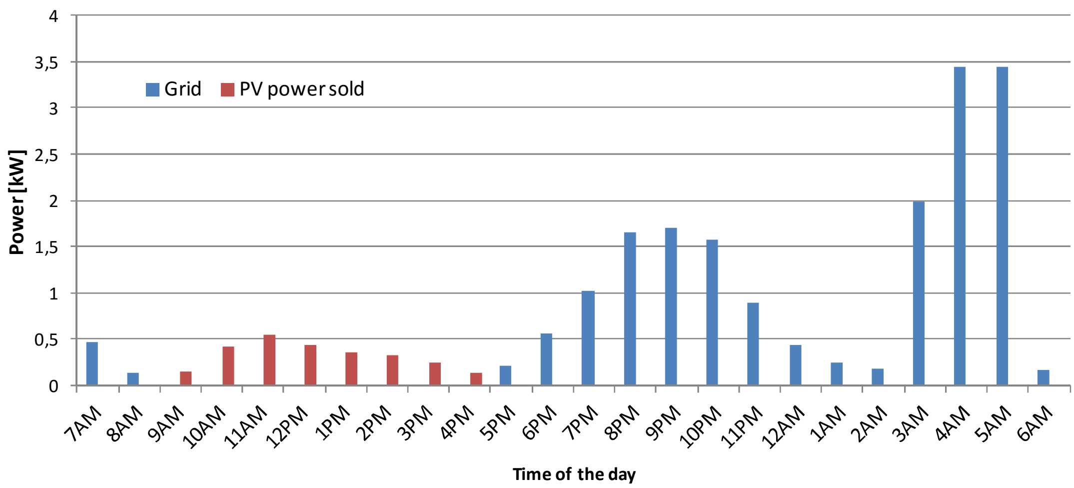


Figure 3.10. The total household power demand for consumers via proposed HEM strategy without EV V2H option.

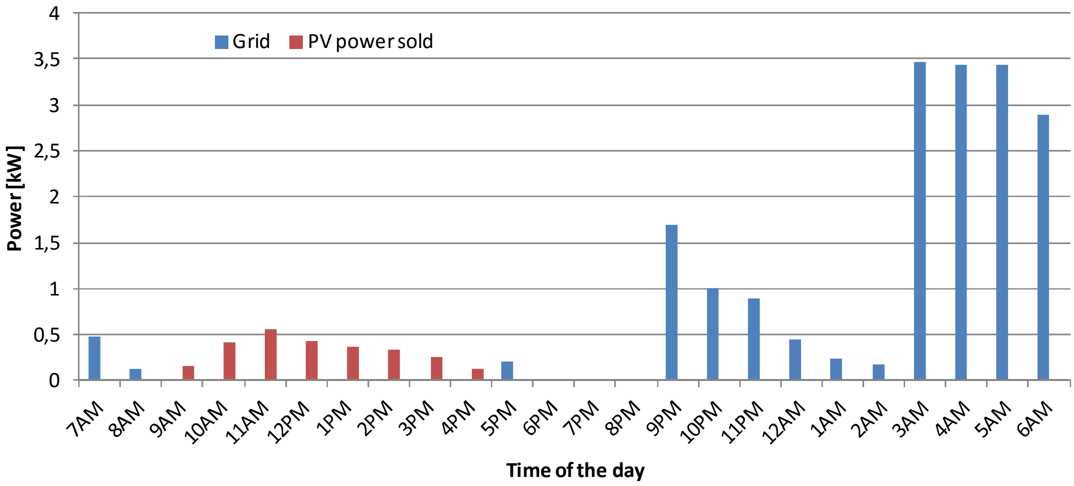


Figure 3.11. The total household power demand for consumers via proposed HEM strategy with EV V2G option.

As the last case study, a household including an additional ESS together with the capability of two-way energy trading with the grid via V2G and ESS-to-grid (ESS2G) options of EV and ESS, apart from the regular V2H and ESS-to-home (ESS2H) operations, is considered. This additional ESS aids the peak clipping and valley filling by charging using power produced by the PV or bought by the grid and discharging in peak price periods. The relevant results concerning the power balance for load supply are presented in Figure 3.13. It is obvious that the ESS and EV supply a varying portion of the load and are charged in off-peak price periods.

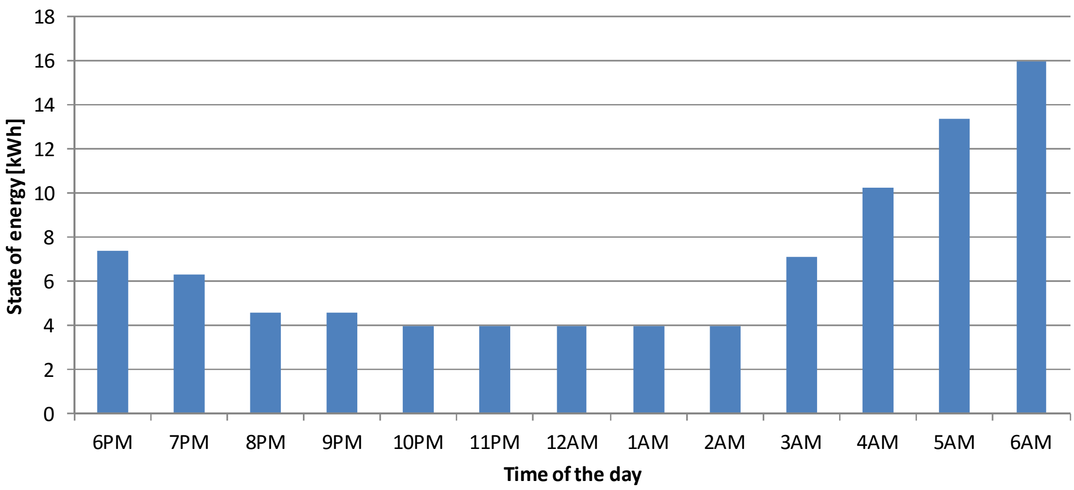


Figure 3.12. EV battery state-of-energy variation for consumers via proposed HEM strategy with EV V2H option.

The corresponding results of ESS and EV state-of-energy are shown in Figure 3.14, where the charging/discharging cycles of ESS and EV are seen in detail, and it is evident that they are directly affected by the flat selling-back to the grid price. It should be noted that the left side y-axis of Figure 3.14 corresponds to the EV state-of-energy interval while the right side y-axis corresponds to the ESS state-of-energy interval. All the case studies based on HEM provide new significant peaks in former off-peak periods till now. As the HEM system automatically shifts the charging of EV to lower price periods, this is likely to happen in real life conditions. Thus, as an extra evaluation under the last case study, a peak power limiting DR strategy is also considered in addition to price based DR strategy that is much likely to be faced in real life as LSE can limit the power that is drawn from the grid in certain peak power periods to avoid more sharp peaks similar to references [170], [171], and [172], respectively.

All the operational possibilities of PV, EV and ESS are still available. This peak power limiting operation is conducted between 7:00pm – 6:00am with a peak power limit of 2kW in this study, and the relevant results are presented in Figure 3.15. Due to the limitations during periods where EV charge is shifted in Figure 3.13, the EV charging has to begin earlier this time in order to have a fully charged EV battery in the morning, which leads to the utilization of more power from the grid in higher price periods. This causes an extra cost which results in a total daily cost of 29.6 cents.

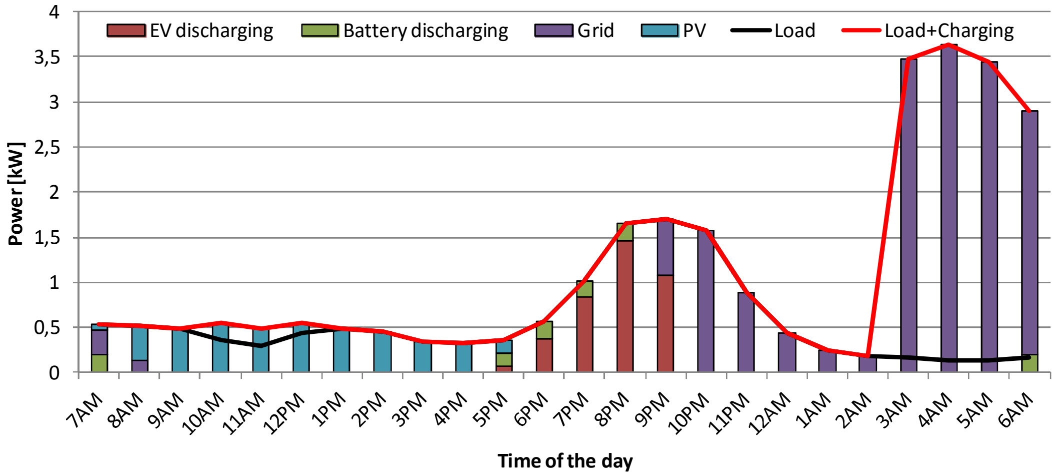


Figure 3.13. Decomposition of household power demand satisfaction via proposed HEM strategy for consumers with EV V2H-V2G and ESS2H-ESS2G options.

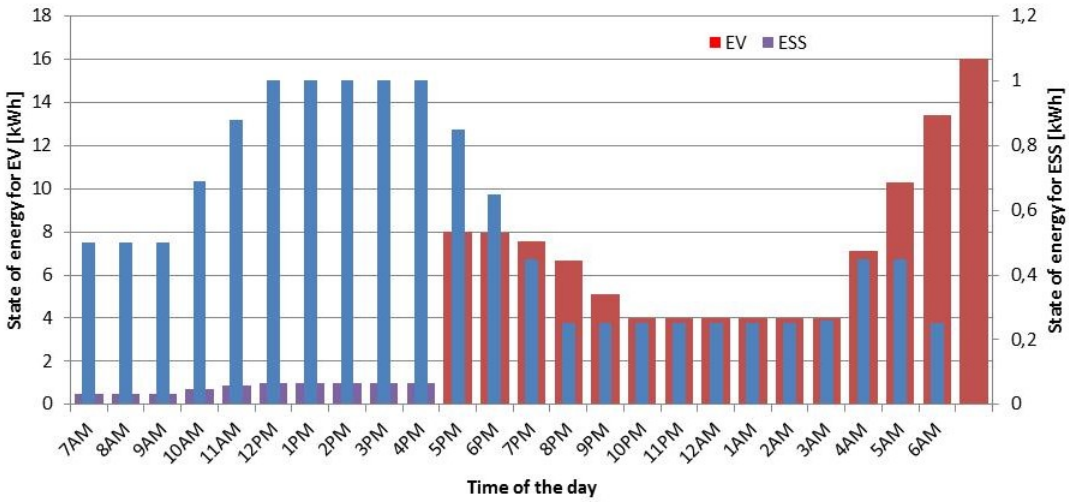


Figure 3.14. EV and ESS state-of-energy variations for consumers with EV V2H-V2G and ESS2H-ESS2G options.

However, in terms of this extra cost, the new peak periods faced in after midnight periods are prevented, as can be seen from Figure 3.15. The comparison of the different case studies is summarized in Table 3.1. It is clear that different consumer preferences in a smart household have a significant impact on daily operating costs. The worst case scenario is considered as consumers having no ESS and willing to charge their EV immediately, which is significantly close to our current daily habits, unfortunately.

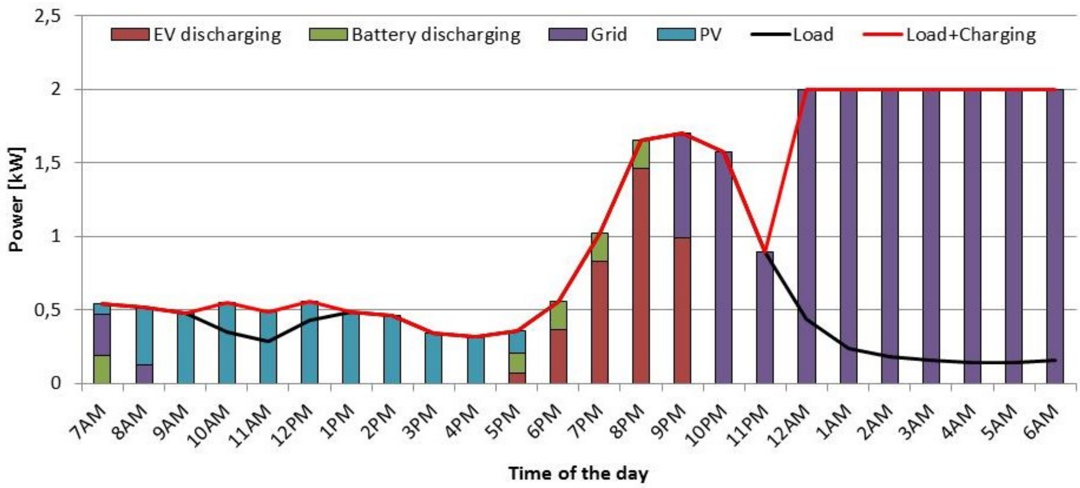


Figure 3.15. Decomposition of household power demand satisfaction via proposed HEM strategy for consumers with EV V2H-V2G and ESS2H-ESS2G options further restricted by peak power limiting DR.

Table 3.1. Comparison of Different Case Studies.

Case Study	Total Price (cents)	Cost Reduction (%)
Consumers willing to charge their EV immediately and without ESS.	58.5	Base case
Consumers willing to charge their EV with lower prices (within the period starting from 10 pm) and without ESS.	51.7	11.6
Consumers willing to charge their EV with lower prices (within the period starting from 2 am) and without ESS.	33.3	43.1
Consumers willing to charge their EV with lower prices together with EV V2H option in peak periods (within the period starting from 10 pm) and without ESS.	49.6	15.2
Consumers willing to charge their EV with lower prices together with EV V2H option in peak periods (within the period starting from 2 am) and without ESS.	30.5	47.9
Proposed HEM strategy without EV V2H option and ESS.	30.7	47.5
Proposed HEM strategy with EV V2H option and without ESS.	21.9	62.5
Proposed HEM strategy with EV V2H-V2G and ESS2H-ESS2G options.	20.3	65.3
Proposed HEM strategy with EV V2H-V2G and ESS2H-ESS2G options further restricted by peak power limiting DR.	29.6	58

Compared to this base case, the total HEM strategy with all opportunities of EV and ESS operation provides a cost reduction of 65.3%. It is also clear that the additional V2G option of EV together with the employment of an extra ESS provides a reduction of nearly 3% compared to the case where HEM strategy with just EV V2H option and without ESS is considered. As mentioned before, the flat rate paid to the household owner for selling energy back to the grid was considered as 3 cents/kWh. Figure 3.16 presents the effect of different flat rates on the decisions of the HEM system for energy exchanges. The flat rates considered in the mentioned evaluation can also be observed from the perspective of the ratio of the selling price to the average buying price, which is 2.93 cents/kWh as derived from Figure 3.4.

Accordingly, these ratios for the considered flat rates of 1, 2, 3, 4, and 5 cents/kWh are respectively calculated as 34.1%, 68.2%, 102.3%, 136.4%, and 170.5%. If the results in Figure 3.16 are examined, the more the flat rate is, the more energy is sold back to the grid. This leads to a more profitable operation, even leading to a minus cost (profit). The prices used in this study are assumption-based and can change from region to region related to many factors. For instance, in restructured power systems, entities that serve the individual loads that do not participate immediately in the market (e.g. aggregators, retailers. etc.) provide a price signal that allows them to maximize their profits in a context of providing the least possible prices to the end-users, so that they can retain them as customers in a competitive environment.

Also, the price at which they are willing to buy electricity back from the end-users (flat or dynamic) is determined by the same rationale. Also, energy pricing can be affected by the state policy that promotes the development of specific technology markets (e.g. like many EU countries have been giving significant economic incentives and subsides in order to promote small and large scale solar energy systems). This study included an off-line optimization that decided the scheduling of appliances for the 24h operation with the assumption of a day before notice for the price signalling and perfect knowledge of the user’s habits. It should be noted that for the proposed technique to be effective, an estimate of the preferences of different EV owners by the LSE can also be necessary. Nevertheless, several solutions to this problem are already provided in the literature by dynamic EV scheduling [180], demographical data based estimation [181], and probabilistic power flow calculations with EV uncertainty [182].

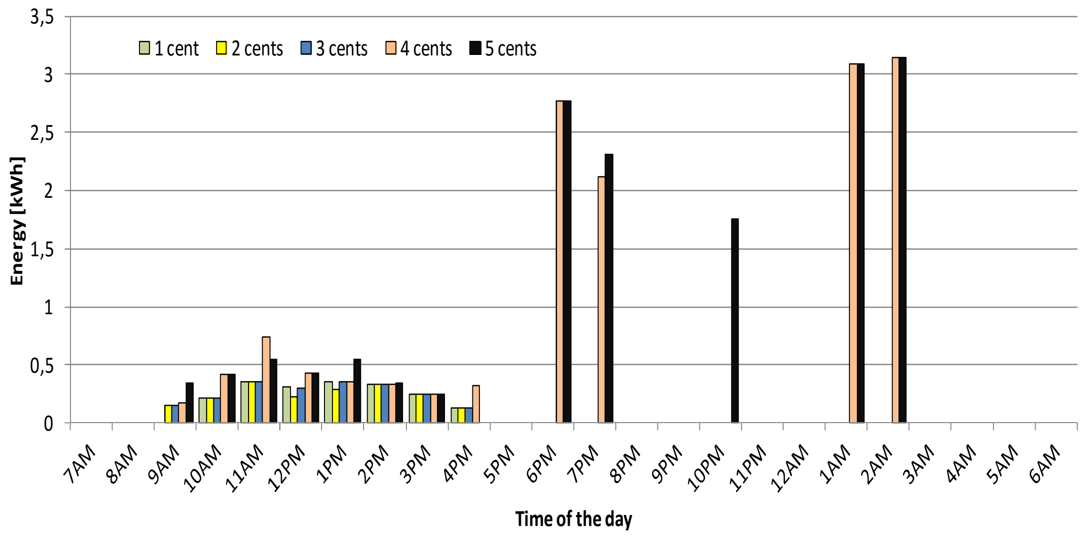


Figure 3.16. Energy sold-selling price relation for consumers with EV V2H-V2G and ESS2H-ESS2G options.

Also, forecasting tools can be successfully employed as part of the smart household infrastructure, which provides detailed data to the LSE from each end-user premise, and in turn can provide enough information to obtain a forecast of the general preferences of EV owners. The key challenge for implementing the proposed idea can be the computational efficiency. It takes just 0.11 seconds to solve the problem for the last case as an example using a Dual Core Laptop with 2GHz CPU and 8GB RAM, which can give an insight of the computation time required for the methodology. The developed model that is utilized in off-line way of application in this study can also be modified to be employed in on-line way by using dynamic programming.

The uncertainty related to the deterministic PV system power production curve in off-line mode can be handled using forecasting tools that are frequently used both in small and big size of applications. The uncertainty of knowledge of dynamic pricing data for upcoming hours can also be solved by shortening the scheduling horizon, considering the horizon of pricing data sent from LSE via smart metering.

Besides, the uncertainties related to the state-of-energy of EV when arriving home can be solved with a second stage of optimization to adopt the operation scheduling via upcoming such as real-time data. Tools such as neural networks could also be fed with daily data and therefore such tools could defer the need for multi-stage programming.

Chapter 4

Wireless Wattmeter Development: Experimental Prototype

This chapter describes in detail a Home Area Network (HAN) based domestic load energy consumption monitoring prototype device as part of an Advanced Metering System (AMS). Such device can be placed on individual loads or configured to measure several loads as a whole. The wireless communication infrastructure is supported on IEEE 805.12.04 radios that run with ZigBee stack. Data acquisition concerning load energy transit is processed in real time and the main electrical parameters are then transmitted through a RF link to a wireless terminal unit, which works as a data logger and as a human-machine interface. Voltage and current sensing are implemented using Hall-effect principle based transducers, while C code is developed on two 16/32-bit MCU.

4.1. Home Communication Architecture and Cloud Based Services

An AMS for home application depends on specialized meters created for the purpose of regular recording of gas and electricity consumption – the smart meter. In turn, the clients will also access monitors called In-Home Displays, which consequently allow them to understand how much power is consumed at any time and how much it is costing them [183].

The obtained data could inspire consumers to utilize less energy, thus reducing their bills and supporting the environment. Clients will also be able to identify when it is more economical to run appliances [184].

The increasing deployment of smart meters to people’s homes results in abundant quantities of data that need to be processed by power distribution company [185]. Cloud computing platforms can bring great scalability and availability concerning network computational resources, bandwidth, and storage.

Notwithstanding, with the installation at a large scale of distributed power meter devices for individualized energy consumption control purposes, an unparalleled increase of data generation arriving in smart meters is expected, which could in turn give rise to severe problems with the quality of service provided by the communication infrastructure between the utility and consumers [186].

Cloud computing could ease smart grid agents' concerns and home owners' apprehension by contributing additional dependable services. This signifies greater scalability and availability of resources concerning network bandwidth, computational resources, and storage. The benefits of introducing the two-way communications of the AMS/Home Area Network (HAN) based power meters with a cloud-based system relate to the information on the house's expected electricity usage behaviour being concentrated and made accessible to a utility, load serving entity or an aggregator, so that those entities being able to perform their optimization processes by guaranteeing precise information to customers [187].

Also, end-user could use a smartphone device to remotely access data concerning their electricity consumption or to set the parameters to the HAN connected domestic appliances in real-time. In addition, from the homeowner's standpoint, the usual domestic computing resources may not be satisfactory to store long-term data. In other words, there is always a risk of it being misplace or corrupted by a defective device [188]. Figure 4.1 presents an overview of a global energy management paradigm through the cloud computing link. As can be observed, the cloud computing infrastructure executes a crucial interface by performing as a virtual decoupler between the smart grid universe and home users, while at same time offering high interoperability concerning communication capabilities.

4.1.1. ZigBee

The ZigBee is a wireless protocol aimed at low power applications that require a low data rate. ZigBee is built on top of the IEEE 802.15.4. The ZigBee norm specifies the higher network layers while the physical and medium control access layers are based on the aforementioned IEEE standard [189]. It can be operated in 2.4GHz, 915MHz or 868MHz bands (license-free ISM band). Data rates of 250kbits can be achieved at 2.4GHz band for each of the 16 channels available in this band.

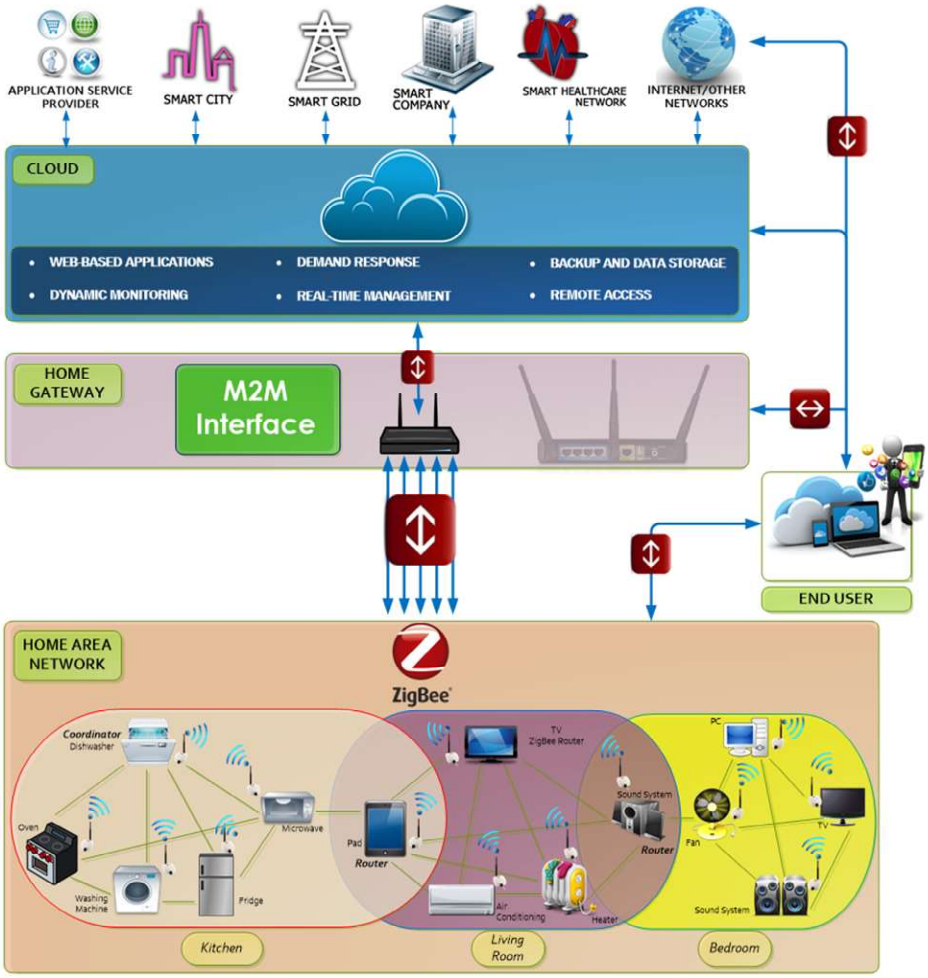


Figure 4.1. AMS/HAN based home energy management system.

Each channel has a fixed bandwidth of 2MHz with a channel separation of 5MHz. The protocol offers high flexibility in terms of network arrangement. The network can be set between the start topology, peer-to-peer communication or mesh networking [190], [191].

4.2. Wireless Wattmeter Design: Block diagram

Figure 4.2 presents the block diagram of a home energy management system based on the wireless wattmeter prototype. The minimum configuration consists of a metering unit built on the MSP432 MCU that performs the power and energy calculations. Aggregated with this unit, a display enables visualization of the real time energy consumption with regard to the appliance being monitored.

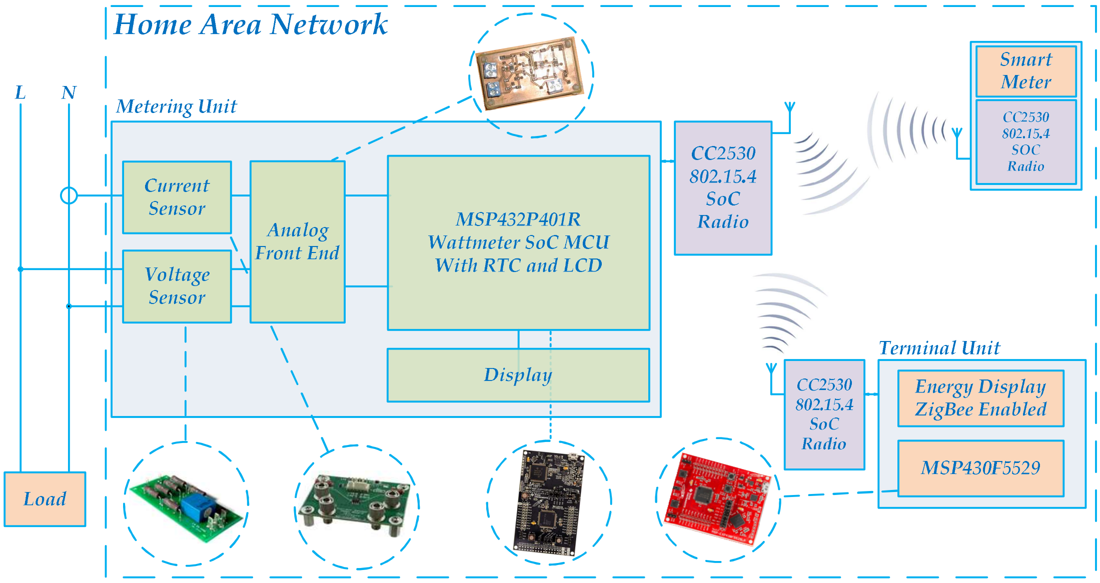


Figure 4.2. Wireless Power meter and terminal unit block diagram.

Plugged to the MCU a CC2530 transceiver sends the energy/power data to a remote unit in charge of gathering the energy consumption profiles from each of the items of domestic equipment being monitored by the power meter. The wireless networking technology is ensured by the ZigBee protocol.

In this work the concept development and experimental tests have been conducted with the metering unit and terminal unit prototypes.

- MSP432P401R and MSP430F5529

The MSP432P401R belongs to a new generation of MCUs with advanced mixed-signal features targeting low power applications, while providing significant performance processing capabilities for moderate signal processing tasks thanks to the ARM 32-bit Cortex M4 RISC engine [192].

Its operating time base can be configured with external or internal clock sources enabling a system clock rate up to 48MHz. It is Analog-Digital Conversion (ADC) capabilities allow data digitization at a maximum conversion rate of 1Msps with configurable resolution from 8 to 14-bit.

In addition, the ADC module allows data to be digitized with only a positive input range (unipolar mode) or by accepting also negative analog signals (bipolar mode).

As for MSP430F5529 model, its features are related with a 16-bit RISC architecture equipped with a rich set of internal peripherals such as four 16-bit timer units, several serial bus interfaces (I2C, SPI and UART modules), and an 8 channels DMA unit. In terms of ADC specifications, it is less flexible and powerful that the ADC available in the MSP432P401R MCU [193].

The conversion module is implemented with a 12-bit Successive Approximation Register (SAR) ADC that can accept only positive input values. The maximum sampling frequency is 200ksps under single channel. When multiple signals are acquired the maximum sampling frequency is shared between the ADC channels. For the metering unit, the MSP432P401R MCU was chosen, while the terminal unit was built on the MSP430F5529 platform [194].

- CC2530 radio

CC2530 is what is known as a system on a chip (SoC). The transceiver functionality and MCU device are merged into a single chip. The radio side contains an IEEE 802.15.4 compliant RF transceiver and MCU function is supported on an 8051 derivate microcontroller featuring 256kB of flash memory, 8kB RAM memory, having also 2 USARTs, 12-Bit ADC, and 21 general-purpose GPIO [195].

Its architecture meets well wireless applications with moderated data processing needs and can be performed by the internal MCU, while at the same time providing a compact solution enabling robust and flexible operation for networking configuration, operation and maintenance due to mesh networking capabilities offered by the ZigBee protocol. ZigBee based wireless applications are gaining increasing acceptance for smart grid and for improving HAN's based AMS functionality [196]. The MCU supports ZigBee, ZigBee PRO, and ZigBeeRF4CE standards.

- ACS712 Current Sensor

A Hall-effect principle operated current sensor is used. Basically, in its outputs has a voltage that is created as function of the directions of both the current and the magnetic field. The main specifications for the current sensor are the radiometric linear output capability, output sensitivity 100 mV/1A (+/-20A), adjustable bandwidth up to 80kHz and low noise analog signal (maximum 92mV_{pp} for bandwidth of 80kHz) [197].

➢ LV 25-400 Voltage Sensor

The mains supply voltage is measured through a LV 25-400 voltage transducer manufactured by LEM. Likewise, it follows the same Hall-effect physical principle translating the voltage reading into a low current value with galvanic isolation between the electric power circuit and the electronic acquisition board [198].

This means a typical analog interface system can be designed to make the bridge between the voltage reading and the MCU. Its main application ranges from alternate current variable speed drives to welding equipment power supplies that demand current monitoring for control and protection purposes [198].

4.3. Metering System Design

Figure 4.3 shows the signal path for voltage and current channels. Due to the internal ADC resources limitation available in the MCU, both channels cannot be digitized at the same time.

The lack of simultaneity on the signal acquisition implies some error due to the voltage and current sampling time difference. However, sampling the channels as close as possible the error introduced can be negligible if the time difference does not surpass 25μs [199].

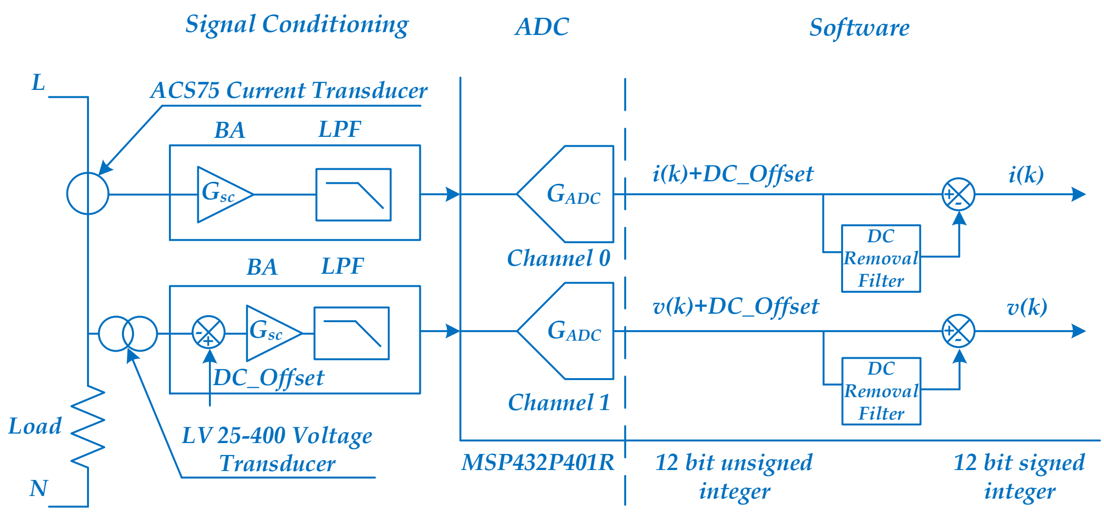


Figure 4.3. Voltage and current signal paths.

- Channel Reading Resolution

The analog signals before being digitized have to be conditioned in order to match their amplitude level with the ADC dynamic range. This function is performed by an individual analog signal chain providing the required conditioning link for each of the two channels. Furthermore, the analog block is also designed with the purpose of preventing the effects of aliasing on sampled data. Amplitude variations in voltage supply are not translated to the output since the sensor gain and offsets are proportional to the supply voltage, V_{CC}, due to the radiometric feature output.

This means the sensitive range is proportional to the supply voltage and for null current measurement the output is $V_{cc}/2$. The current sensor is supplied with 2.5V corresponding to the MSP432P401R ADC internal voltage reference. This option simplifies the instrumentation chain design. The transfer function for the current measurement is Equation (4.1), where V_{IS} is the output voltage, K_{CT} is the traducer gain, I_{Load} is the sensed current and V_{OC} is the offset voltage related to the transducer zero current [200].

$$V_{IS} = K_{CT} I_{Load} + V_{OC} \tag{4.1}$$

Thus, the voltage at ADC input is given by Equation (4.2), where K_{CS} is the signal conditioning circuit gain [201].

$$V_{IS\_ADC} = K_{CS}(K_{CS} I_{Load} + V_{OC}) \tag{4.2}$$

The resolution of the sampled data is Equation (4.3), where N_{code} is the ADC code, M is the ADC resolution and G_{ADC} is the ADC gain. A similar approach can be made for the voltage measurement channel.

$$N_{code} = G_{ADC} V_{IS\_ADC} = \frac{2^M}{2.5} V_{IS\_ADC} \tag{4.3}$$

In measuring electrical quantities the choice of the ADC has a crucial role on the accuracy of the power meter. By norm, commercial power metering solutions incorporate 24-bit ADCs. This high level of resolution is mandatory to fulfill international standards such as EN 50470-1:2006 or EN 50470-3:2006 [202]. Most MCU manufactures are now offering internal ADC with up to 24-bit (Sigma delta converter).

However, their effective bit resolution is lower than announced, since the internal MCU noise prevents this level of resolution being achieved for the highest sampling rate. To avoid high costs due to implementation of a discrete 24-bit ADC chip, the power meter proposed takes advantage of the MCU's internal ADC. However, by taking this approach the resolution available is considerably lower. In fact, the MSP432P401R comes with a 14-bit ADC [194]. The voltage channel is dimensioned for 300V as the nominal RMS reading, which translates into a maximum voltage peak-to-peak measurement of:

$$U_{pk-to-pk} = 300 \times \sqrt{2} \times 2 = 848V \tag{4.4}$$

Given that the noise-free resolution is 12-bit for MSP432P401R ADC in unipolar operation, the accuracy of the conversion corresponds to 0.02% of the full scale ADC range. Therefore, the lowest value of the voltage at which the power meter is able to read is:

$$U_{LSB:peak\ to\ peak} = 848V \times 0.0002 = 0.17V \tag{4.5}$$

$$U_{LSB:RMS} = 300V \times 0.0002 = 0.06\ V \tag{4.6}$$

- Antialiasing filter requirements

According to Shannon's theorem, any digitized signal must be acquired with a minimum signal sampling f_s of twice the bandwidth signal. The failure to comply with this rule implies that the analog signal cannot be fully reconstructed from the input signal. Moreover, it introduces low frequency terms on the digitized signal that comes from the high frequency components above the sampling frequency.

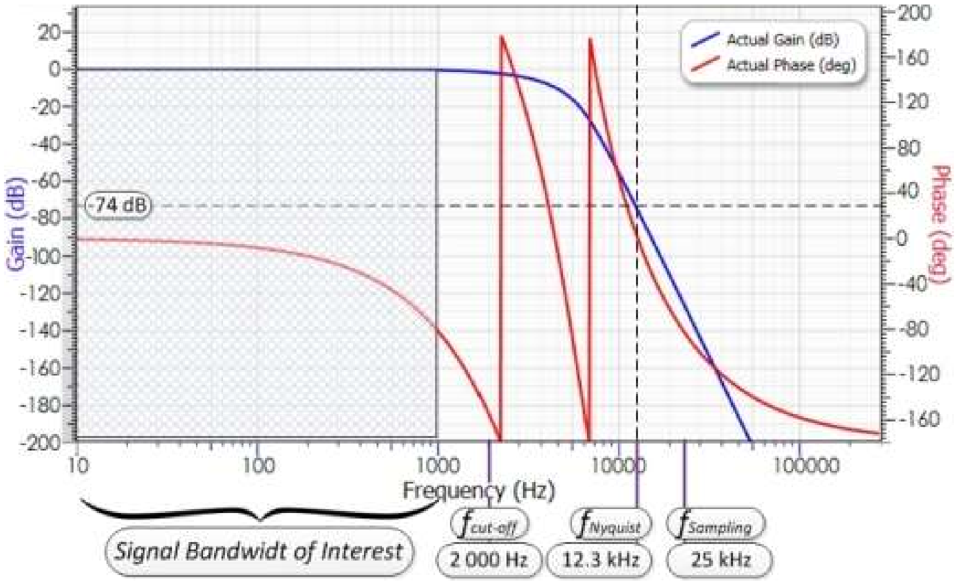
This phenomenon is known as aliasing. Also the filter displays the function of removing high frequency noise. In fact, all electronic front end (AFE) systems generates broadband noise which affects the effective dynamic range for data acquisition [203].

For the power metering device in development, it was defined to set the signal's useful acquisition bandwidth up to 1000Hz. That is to say, the voltage and current signals are acquired taking into account their harmonic content. Given that the power grid frequency is 50Hz, then the acquisition bandwidth specification enables harmonic measurements up to the 20th order. To accomplish this, a low pass filter is required to limit both electric signals in terms of bandwidth [203].

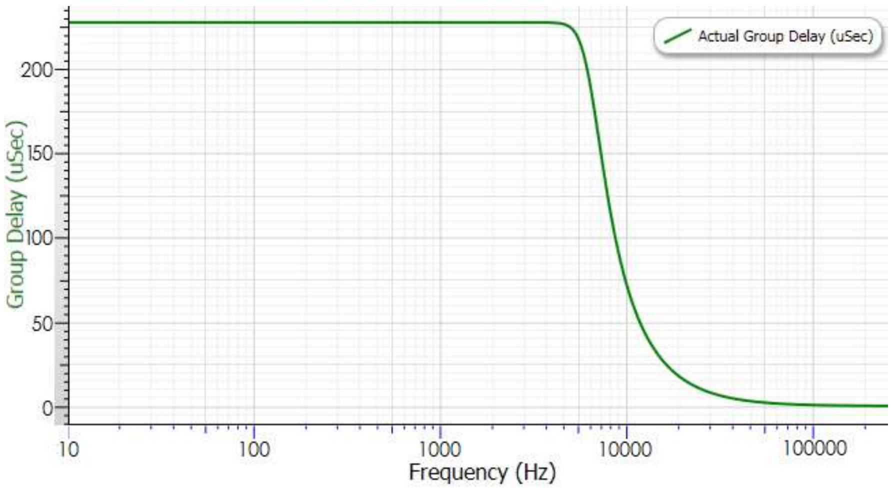
The choice of a Bessel analog filter presents one particular advantage over the other filter topologies – the filter's group delay is approximately constant across the entire pass-band, this being a critical design specification to minimize the effect of distortion on digitized signals. To guarantee a negligible attenuation at 1000Hz, which makes up the useful bandwidth of acquisition, the filter cut-off frequency is defined as 2000Hz.

To take full advantage of the analog-digital converter (ADC's) dynamic range, which is characterized by its signal-to-noise ratio (SNR) [14], several design criteria must be considered to match the AFE with the ADC performance. The MSP432 14-bit ADC provides an effective resolution slightly higher than 12-bit at unipolar operation [192], which means the ADC SNR is 74dB. To achieve the maximum dynamic range from AFE circuit, the RMS noise levels and aliasing effects at the ADC input have to be minimized below the ADC noise floor.

For this a high order Bessel filter was designed in order to reduce the sampling frequency requirement overloading the MCU code execution.
As a result, a 10th order Bessel filter matches the attenuation requirement at approximately 12.3kHz. Then, the Nyquist's Frequency ($f_s/2$) can be associated with this frequency and the sampling rate is approximately doubled to comply with Shannon's theorem. Bessel filter frequency response is shown in Figure 4.4. The implementation of the conditioning circuit combined with the anti-aliasing filter is depicted in Figure 4.5 [204].



a)



b)

Figure 4.4. 10th order Bessel Filter frequency response: a) Magnitude and phase; b) Group delay.

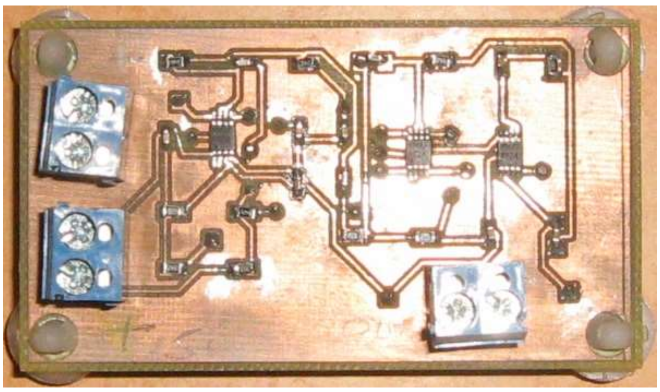


Figure 4.5. Analog front end board.

- Post-acquisition digital filter for DC offset removal

Voltage and current waveforms are digitized using the MSP432's ADC unipolar single-ended inputs, because the instrumentation chains translate the electrical magnitude signals into a positive scale of values. Consequently, the unsigned digitized signals from the voltage and current measurements must be converted into signed integer format in order to proceed to the characterization of the electrical quantities associated with the load energy transit [205]. One common strategy is to fill a data buffer with a specific number of samples and then estimate the offset term by calculating the average of the samples. If the analog chain output provides a stable DC bias point, then it is simply assumed to be a constant offset term, meaning that each ADC sample is immediately subtracted to this fixed term. Both approaches have their pros and cons. A data buffer offers an effective way of removing DC content [206].

However its implementation demands considerable memory resources whose availability is scarce in low-end MCUs. Hence, the second choice, despite being the simplest option, has a limited applicability since the AFE DC offset output signal may vary in an unpredictable way, thus jeopardizing the result. Moreover, the noise generated inside the signal chain may also have an impact on DC bias point stability over time [207]. An alternative possibility requires a high pass digital filter for the job. The filter performs the offset removal in real time enabling immediate use of the electrical quantity calculation algorithms. Generally, an Infinite Impulse Response (IIR) filter provides a lower design for same filtering techniques and it can be the best choice if sharp response low-pass magnitude output is required. To maintain low signal processing resources requirements, a first order IIR filter is implemented with the following discrete transfer function [208]:

$$H(z) = \frac{0.996 - 0.996z^{-1}}{1 - 0.996z^{-1}} \tag{4.7}$$

Then, the difference equation for code execution is:

$$y[n] = 0.996 \times y[n-1] + 0.996 \times x[n] - 0.996 \times x[n-1] \tag{4.8}$$

The filter transient response settle to within 1% of its final value around 1000 samples. The input samples and coefficients are both 32-bit arithmetic fixed points and signed to suppress the effects of binary word length on filter's outcome performance.

- RMS

Mathematical definition for the RMS of an analog signal *x(t)* is Equation (4.9), where T is the acquisition time window. On the other hand, digital RMS calculation is Equation (4.10), where V_k is the voltage sample at instant k and M is the time window [209].

$$V_{RMS\_analog} = \sqrt{\frac{1}{T}\int_0^T x^2(t)dt} \tag{4.9}$$

$$V_{RMS\_discrte} = \sqrt{\frac{\sum_{k=1}^{M} V_k^2}{M}} \tag{4.10}$$

Digital RMS estimation is described by two operations. One is to square the samples as they are acquired. The other involves the use of an averaging filter to extract the dc component of V_k^2 with a low pass filter. The discrete transfer function is presented below [210]:

$$H(z) = \frac{2^{-p}}{1-(1+2^{-p})Z^{-1}} \tag{4.11}$$

where p factor is used to determine the cut-off frequency of the IIR filter which is calculated by Equation (4.12), where f_s is the sampling frequency. Selecting a cut-off frequency of circa 1.9Hz with a sampling rate of 25ksps the Equation (4.12) output a p value of 11.

$$F_c = \frac{2^{-p}}{2\pi} f_s \tag{4.12}$$

- Active power measurement

The instantaneous current $i[n]$ and voltage $u[n]$ samples are multiplied which result in what is called the instantaneous power $p[n]$. Next, it goes through a low pass filter in order to extract the DC component which represents the average active power consumed by the load. A 10Hz cut-off frequency single pole IIR filter is chosen. Its discrete function is given by the Equation (4.13) [211].

Then, the difference equation form is Equation (4.14). However, Residual ripple at twice the power grid frequency is present in the filter's digital output due to the instantaneous power signal. Further processing to calculate the energy consumed will remove it because the ripple is sinusoidal in nature [211].

$$(z) = \frac{0.030 - 0.03z^{-1}}{1 - 0.939z^{-1}} \tag{4.13}$$

$$y[n] = 0.939 \times y[n-1] + 0.03 \times x[n] - 0.03 \times x[n-1] \tag{4.14}$$

- Reactive power measurement

For steady power grid frequency and linear time-invariant loads, the voltage and current signals are pure tones. That is to say, there are no harmonics or mixing products, which means it is only necessary to shift one of the waveforms by 90 degrees in relation to the other waveform. Normally, the grid voltage signal has low harmonic content but the current signal does not. Furthermore, the delay needs to be accurate to ensure good results. Reactive power instantaneous value for $n-th$ harmonic is described by the Equation (4.15) and then the total reactive power is described by the Equation (4.16) [212].

$$Q_n = 2V_m I_m sin\theta \sin\left(\theta - \varphi + \frac{\pi}{2}\right) \tag{4.15}$$

$$Q = \frac{1}{2}\sum_{n=1}^{N} V_n I_n sin\varphi_n \tag{4.16}$$

The Hilbert transform of a waveform is given by the Equation (4.17). The transformer operator allows each signal frequency component to be shifted at $\pi/2$ while the respective magnitude is preserved. In other words, when applied to a function, it introduces a phase delay of $\pi/2$ on positive frequency components and a phase advance of $\pi/2$ on negative frequency components [213].

$$H[x(t)] = \frac{1}{\pi} \int \frac{x(s)}{t-s} dt \tag{4.17}$$

Its implementation is normally done through a linear filter. The transfer function is given by Equation (4.18). Since ideal Hilbert transform shows an infinite impulse response, its applicability is not viable. Hence, to limit the impulse response length a practical Hilbert transform implementation must be approximated through a linear-phase FIR filter [214].

$$H(e^{jw}) = \begin{cases} -j, & 0 < w < \pi \\ j, & -\pi < w < 0 \end{cases} \tag{4.18}$$

To aforementioned propose, the FIR filter design needs to define a finite size window that corresponds to a filter of order N. The FIR filter specification based on the window approach means that the window weight coefficients throws away the Hilbert coefficients that are outside the window. A window function that can be approximated as an ideal window can be achieved by combining a Kaiser window with hyperbolic-sine function. The Kaiser window is expressed by the Equation (4.19), where $\beta = w_a \mathrm{M}/2$ and I_o is the zerot-order modified Bessel function of the first level [215].

$$w_k(n) = \begin{cases} \dfrac{I_o\left[\beta\sqrt{1-\left(\frac{2n}{M}\right)^2}\right]}{I_o(\beta)}, & |n| \leq \dfrac{M}{2} \\ 0, & |n| > \dfrac{M}{2} \end{cases} \tag{4.19}$$

Normally, the value of the parameter β is selected according to the desired filter characteristics. The window length is determined by $N = 2M + 1$ where M is the constant group delay. Usually, FIR filters are designed as casual filters. Therefore, the Hilbert FIR filter phase is equal to Hilbert phase response plus a linear phase term with a slope equal to M. For practical calculations the desired magnitude and phase characteristics of FIR Hilbert filter were obtained by setting the Kaiser window with a filter length $N = 21$ and $\beta = 4$ [215].

- Active energy

The active power time series is integrated over the time in order to provide the energy consumption profile. The integral operation in the digital domain is carried out by using a first order IIR digital integrator based on Backward Euler method according to Equation (4.20), where, $\Delta t = 1/f_s$, it is the sampling time and the instant k is related to the current sample while instant $k-1$ refers to the previous sampling instant.

$$Wh[k] = Wh[k-1] + \frac{U[k] \times I[k] \times \Delta t}{3600} \tag{4.20}$$

- Reactive energy

The reactive energy is performed in analog domain as an infinite integral of the instantaneous shifted phase voltage delayed by 90º and phase current signal given by [216]:

$$VARh = \frac{1}{3600}\int_0^{\infty} u(t - 90^{\circ})i(t)dt \tag{4.21}$$

Applying Backward Euler rule to approximate the integral term in discrete domain and using the Hilbert transformer, it follows by the Equation (4.22), where $\Delta t = 1/f_s$ is the sampling time, $U_{-90}[k]$ [217].

$$VARh[k] = VARh[k-1] + \frac{u_{-9}\ [k] \times i[k] \times \Delta t}{3600} \qquad (4.22)$$

4.4. Experimental Results

The testing procedures consist on evaluating the readings facing two type of loads in order to check the measurement performance, whether the load is linear or not-linear. With regards to the linear load, an electric heater commonly found in households is chosen. For non-linear testing an AC-DC adaptor connected to a network computer is used. A general view of the experimental test bench is shown in Figure 4.6.

4.4.1. Linear load

The electric heater has a rated power of 1200W regulated as a function of three power setting levels available. When the maximum power is not required the user can select the 400W or 800W mode. The tests focused on comparing the current waveform acquired by the power meter developed with the wave trace observed on an oscilloscope. For current measurement, digital sample set acquisitions and post processing techniques are synchronized with the bench instruments. The idea is to get comparable electric quantity calculations on the same time windows using an accurate current meter.

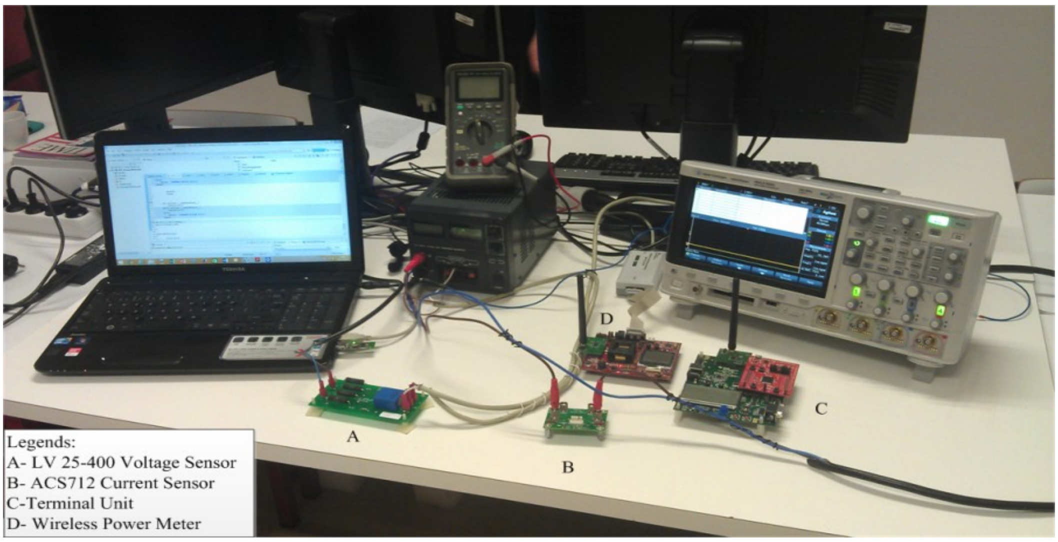


Figure 4.6. Experimental test bench.

Keysight 34461A 6.5 digit precision multimeter was employed to determine current RMS values at minimum, medium and full power. These measures made it possible to assess the prototype RMS estimation capabilities. In addition, several oscilloscope graphs were taken concerning the voltage and current readings. Figure 4.7 shows the mains voltage waveform. The distortion apparently seen on the waveform is not caused by the load, yet it is visible. In fact, the mains grid into which the electric heater is plugged has non-zero output impedance, depending on the equipment connected to the power grid, such as light ballasts, motors and so on. Figure 4.8, Figure 4.9 and Figure 4.10, show the current waveforms in respect of the three levels of power consumption illustrated at different levels of signal processing chain. In the first part of each figure the impact of analog filtering can be observed.

The second part of the figure is related to the readings in digital format after being acquired by the ADC. Figure 4.8 the measured current (green trace) looks noisy. In fact, more than 20mV was measured as peak-to-peak noise. This level of noise limits the sensor’s sensitivity. That is, for a sensitivity ratio of 100mV/1A, lower readings than 20mA are virtually impossible to track and distinguish. The anti-aliasing filter (blue trace) proves to be effective by cutting most of wideband noise outside the filter bandwidth that comes from the output sensor. As the electric heater is switched from the lowest power level to the highest power settings, the pre-filtered noise content has less influence on measurement resolution.

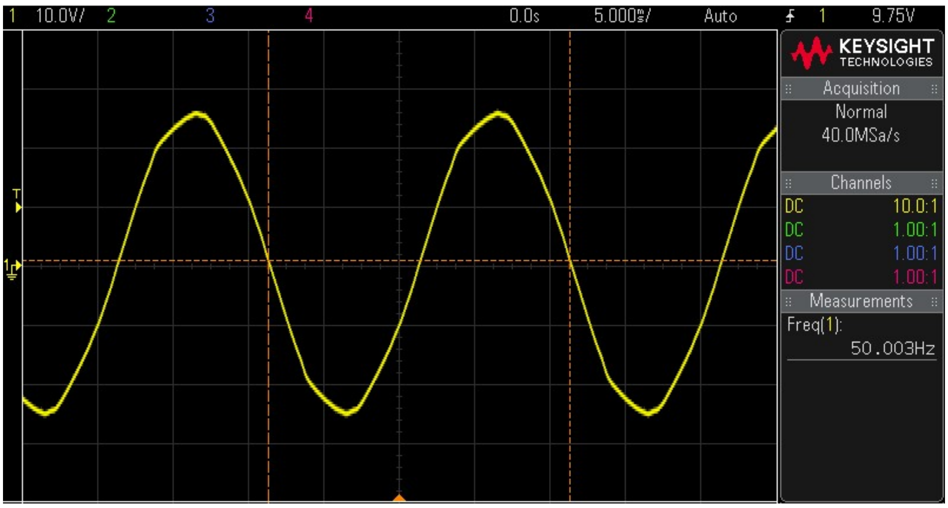
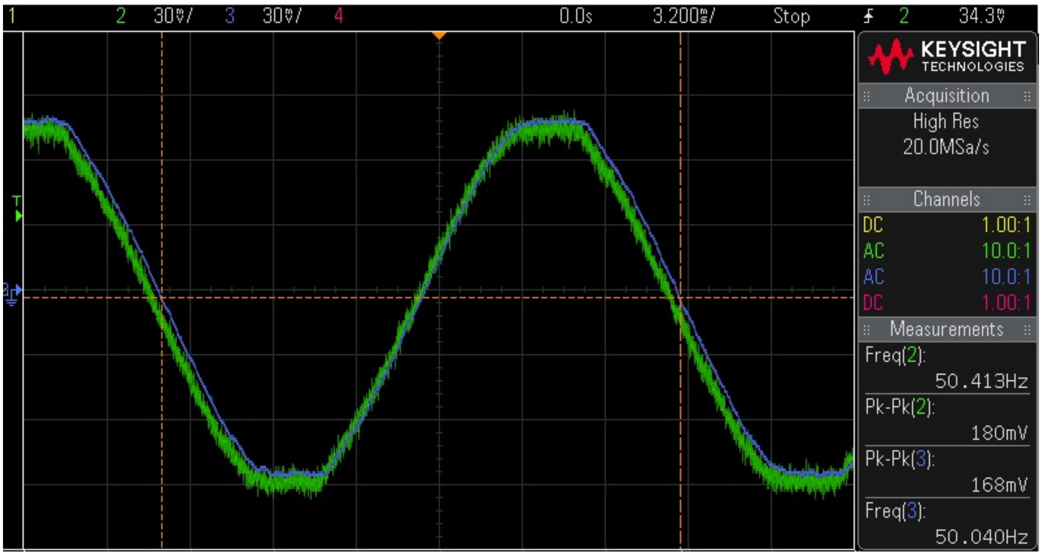
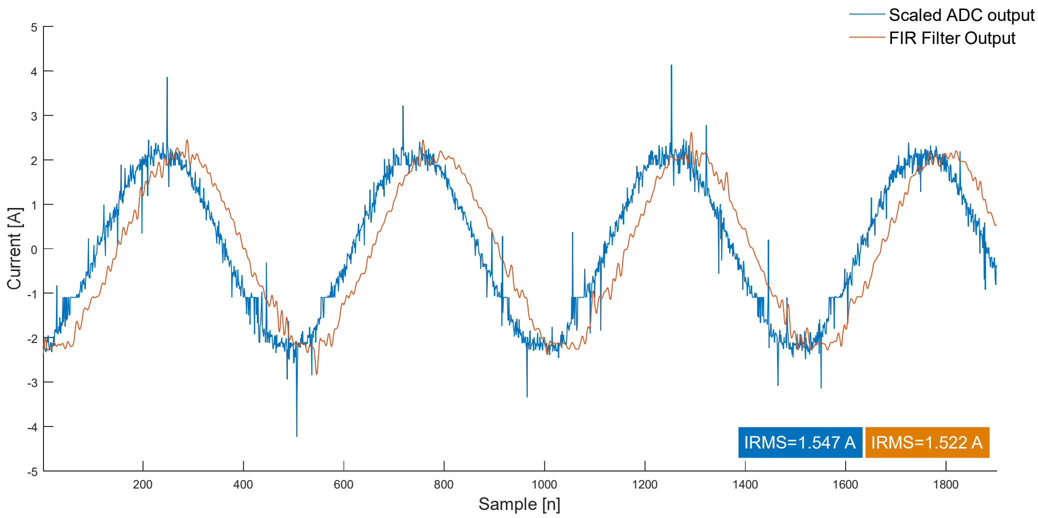


Figure 4.7. Mains voltage reading.

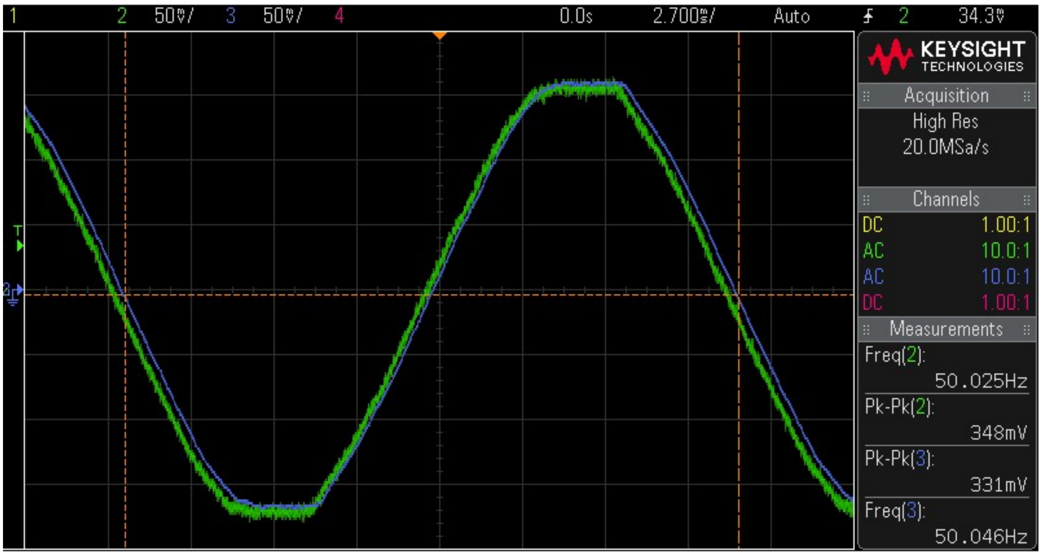


a)

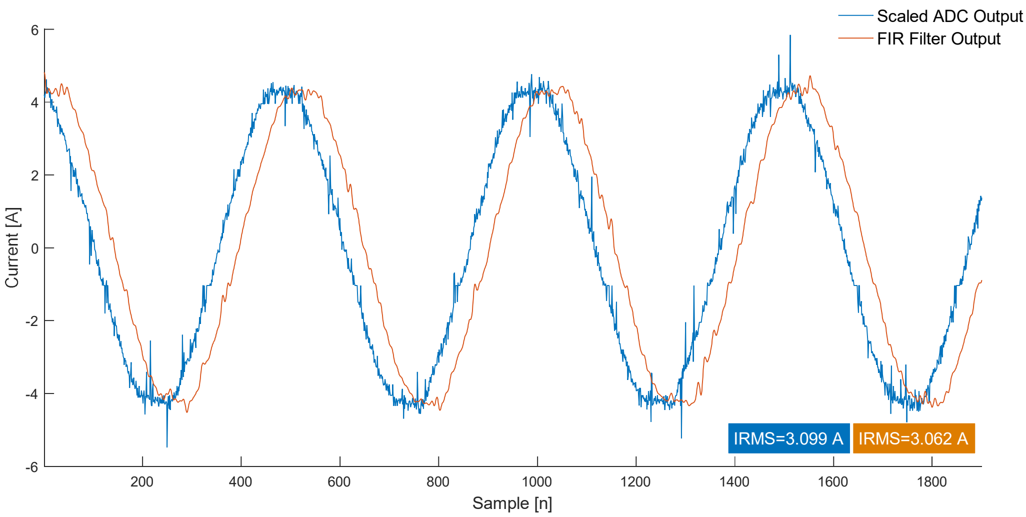


b)

Figure 4.8. Electric heater at minimum power: a) Current reading before and after analog filtering; b) ADC current reading and post processing 80 tap linear-phase FIR filter.

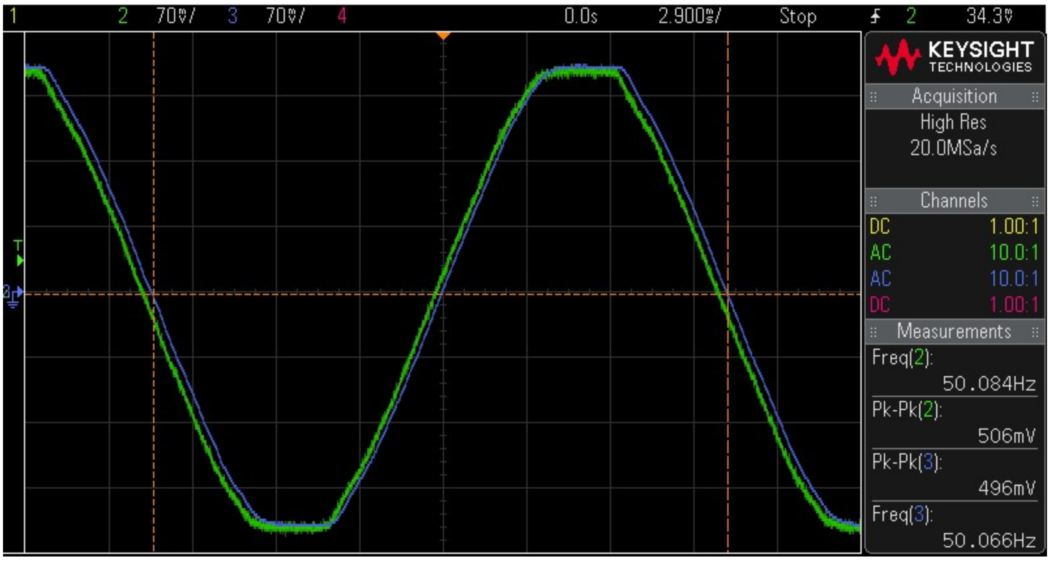


a)

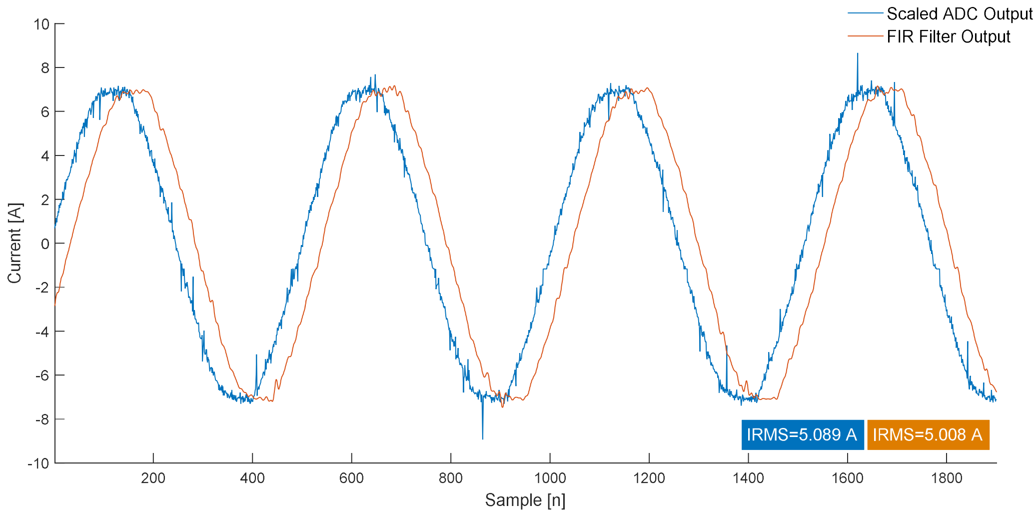


b)

Figure 4.9. Electric heater at medium power: a) Current reading before and after analog filtering; b) ADC current reading and post processing 80 tap linear-phase FIR filter.



a)



b)

Figure 4.10. Electric heater at full power: a) Current reading before and after analog filtering; b) ADC current reading and post processing 80 tap linear-phase FIR filter.

In sum, when acquiring low amplitude currents the anti-aliasing filter has the important function of improving the signal-to-noise ratio of the readings. In turn, the sampled current data have considerable spikes on the samples (Figure 4.8 b), Figure 4.9 b), and Figure 4.10 b), the blue line respectively). The severity of the spikes is more significant for electrical quantity calculations such as RMS measurement. In aforementioned figures the RMS estimations are illustrated and compared when the discrete data is passed through a digital filter of 80 tap. The band cut-off frequency (2100Hz) chosen is slightly higher than the anti-alias filter bandwidth. The RMS computation based on raw scaled ADC data exceeds by 1.6% the value found after the current samples have been smoothed by the digital filter.

The magnitude of the error is small from this particular viewpoint, considering that it is designing a power meter for residential usage. However, its impact on successive computations when performing active and reactive energy calculations will accumulate as instantaneous power estimations and summed over the computation time frame. Hence, the error propagation effect will inflate the data integration operated electrical quantities. A simplified bench calibration procedure using a 6.5-digit precision multimeter reduced the RMS estimation error to less than 0.1%. Therefore, for single electrical quantity calculation, the performance achieved is quite remarkable if it takes into account the level of digital discretization available from the internal ADC resource. Naturally, the discrepancies found in prototype readings concerning the other electrical quantities have to be confirmed with more tests covering a wider group of electric loads and testing conditions.

4.4.2. Non-linear load

The DC power for a laptop is commonly derived from a single-phase full-wave diode bridge rectifier connected to the alternate current line, followed by a DC-to-DC power conversion stage called the switch-mode power supply. This AC–DC converter technology has gained wide acceptance, providing a smooth DC output with small and lightweight components. In addition, power supplies of this type tolerate large variations on input voltage [218].

Figures 4.11 and Figure 4.12 illustrate the current waveform readings before and after analog filtering. In Figure 4.11 the laptop is not running any specific program application. It can be seen that the input current comes in very short pulses as the capacitor is charged on a tiny half-cycle fraction. When executing Windows-based application like a video file player, the current waveform is less sharp, as can be verified in Figure 4.12.

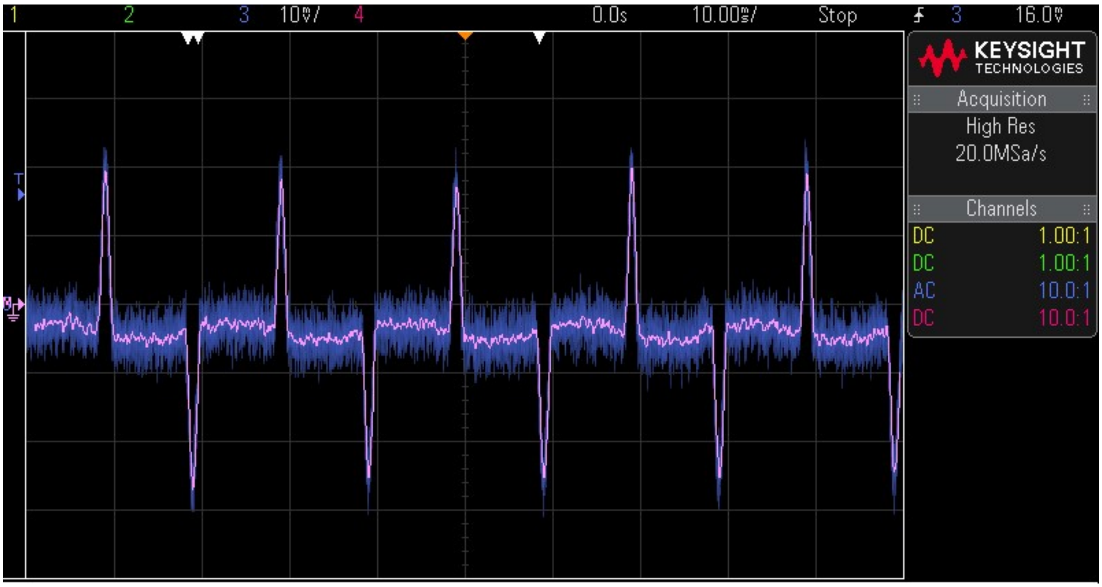


Figure 4.11. Current waveform readings before analog filtering.

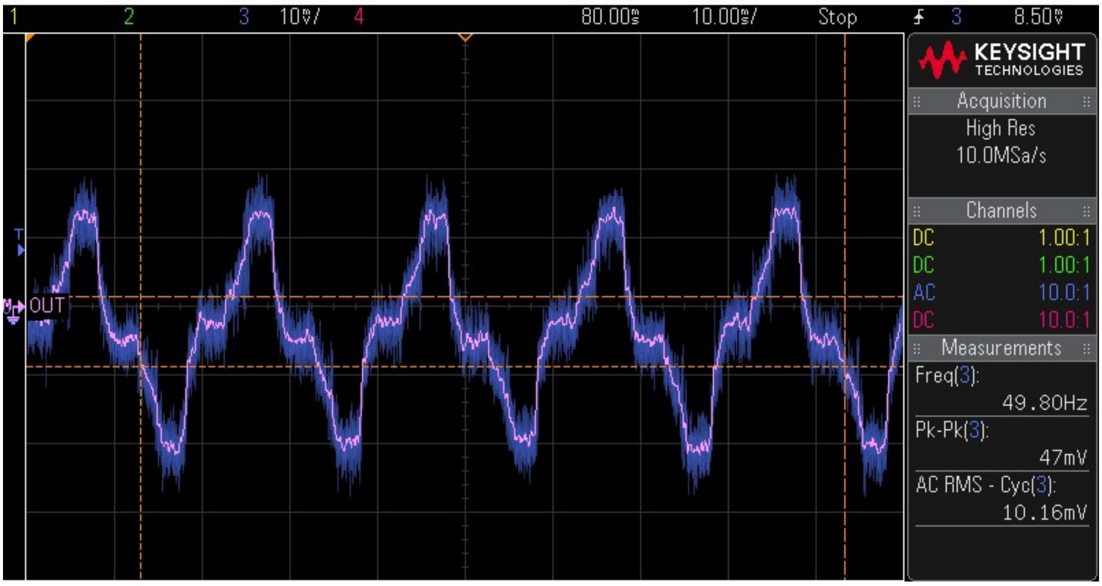


Figure 4.12. Current waveform readings after analog filtering.

In sum, in light load conditions the input current tends to be more distorted, revealing a higher current peak. Moreover, the AFE circuit extracts significant noise superimposed on the current signal.

For such low load current measurements, the AFE has a dramatic effect, since the current works addresses an AC–DC adaptor maximum input current of 1.5A, which corresponds to 7.5% of the dynamic range specified on the power meter. Next, a second AC–DC connected to another laptop was analyzed, revealing a different input current pattern.

For the last aforementioned case, the peak current measured falls below 1A, exposing the level of noise aggregated to the sampled current at 25ksps. Even after being processed by the FIR filter, the level of noise remains considerably high. Increasing the complexity of the digital filtering may not be a good choice because the MCU will spend more time on performing digital filtering.

Therefore, a simple moving average filter can solve most of the noise issues at this measurement level. In Figure 4.13, is illustrated ADC current reading and post processing 80 tap linear-phase FIR filter.

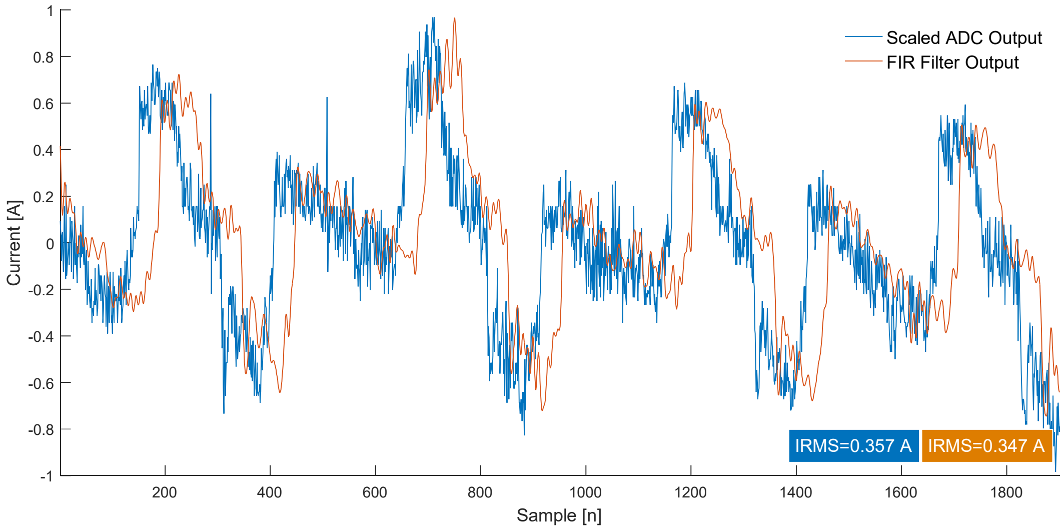


Figure 4.13. AC-DC adapter input current: ADC current reading and post processing 80 tap linear-phase FIR filter.

Chapter 5

Model Predictive Control for Home Energy Management

The main objective of this chapter is to apply an innovative form to control the loads in order to optimize energy consumption in the residential sector, whereby facilitating the consumers to provide complete information about their energy consumption and respective cost. Two case studies are provided: the first case, Case A, determines the impact of model predictive control (MPC) on energy savings for residential households. Furthermore, the value and impact of power generated by local power sources, such as rooftop solar panels, will be determined during off-peak, mid-peak, and on-peak periods, providing simulations during 24 hours in a house. The second case, Case B, demonstrates the impact of optimization technologies on the energy savings of residential households. In this regard, a MPC approach is proposed for home cooling and heating systems. Its effectiveness is compared with a conventional thermostat control, providing also simulations during 24 hours.

5.1. System Model

The system that was used to simulate the predictive control technique was applied to some residential loads such as air conditioning, thermostat and fridge. All these charges were modeled to resemble as close as possible to reality. Modeling a house data features are deeply influenced by the thermal properties of each constituent element, taking into account that the energy consumption is dictated by the thermal response of each material [219]. Thus, as will be seen, the retention of hot air/cold in the house depends on the characteristics of each material. As we consider the house as a whole, their performance varies widely depending on the geometry of each division. Equation (5.1) where C is the heat capacity of each material, the property that measures heat storage capability.

This heat capacity C is defined as the amount of energy required to raise the temperature of a unit mass of a substance, Q is the heat transferred to the sample, m the mass, and ΔT the resultant variation temperature. Analogously, one can calculate that capacity per unit volume being by Equation (5.2), where V is the sample volume [220].

$$C = \frac{Q}{m\,\Delta T} \tag{5.1}$$

$$C_v = \frac{Q}{V\,\Delta T} \tag{5.2}$$

However, volumetric heat capacity is related to the c_p specific heat and density ρ, then it follows by the Equation (5.3). In addition to the thermal capacity of each material, there is heat loss due to the thermal resistance of each material. The driving is a mode of energy transfer that occurs through energy particles with adjacent substance that has a lower level of energy, and can be expressed according to the heat conduction Fourier Law [221], expressed by Equation (5.4), where the amount of heat transferred per unit time is given by $\dot{Q}$, k is the thermal conductivity, A is the normal area to the direction of heat transfer and dT/dx the temperature gradient.

$$C_v = \rho \times c_p \left(\frac{J}{m^3\,K}\right) \tag{5.3}$$

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \tag{5.4}$$

To obtain the heat transferred per unit area that through the Equation (5.5) considering stationary heat conduction through a sufficiently large surface with a thickness $\Delta x = L$, area A and temperature difference along the wall $\Delta T = T_2 - T_1$, it is considered the Equation (5.6) where the heat flow q that passes through the glass of thickness L is proportional to ΔT (temperature difference) which can be expressed as well by Equation (5.7).

Meanwhile, Equation (5.8) R express the heat transfer resistance, because each material will respond with a different resistivity to the heat flow that is imposed.

$$\frac{q}{A} = -k\frac{dT}{dx} \tag{5.5}$$

$$q = kA\frac{\Delta T}{L} \tag{5.6}$$

$$q = \frac{\Delta T}{R} \tag{5.7}$$

$$R = \frac{L}{kA}\left(\frac{W}{K}\right) \tag{5.8}$$

Figure 5.1 depicts the circuit model used to represent a house division, where T_{out} is considered as the outside temperature, the thermal characteristics of the house division are characterized by R_w and R_c as the heat resistance of the walls and windows respectively. The thermal capacity of the walls is represented by C_w and indoor air by C_i. The source that draws heat is identified as Q_{ac_ht}, and Q_{in} is the heat to be removed. In turn S represents a binary variable used for bound states ON (1) and OFF (0). Q_s represents the transfer of heat to the house through solar radiation. In Figure 5.2, represent a wall of a house, where, the R value is proportional to the length L in the direction of heat transfer, and inversely proportional to the heat transfer surface area A and its thermal conductivity k.

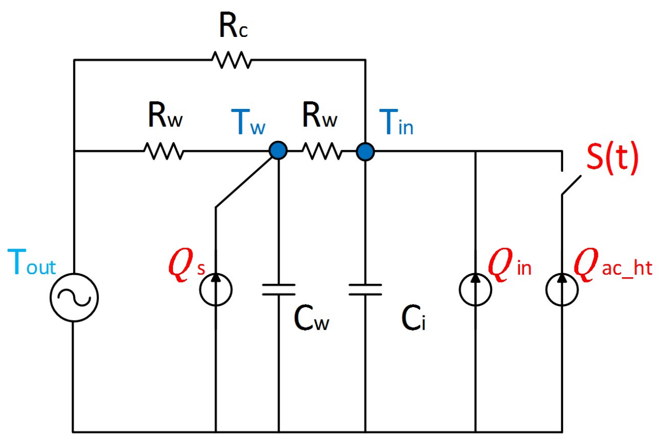


Figure 5.1. Equivalent thermal circuit for a division, adapted from [222].

However, to be considered the references [220], [223], it can obtain the following differential Equations (5.9) and Equation (5.10), respectively. The properties of the materials in buildings greatly influence energy consumption and as consequence, results in different thermal conductivity: the walls, the floor, the roof and the windows. To obtain the values of capacity and thermal resistance Equation (5.9) and Equation (5.10) are used providing the information presented in Table 5.1.

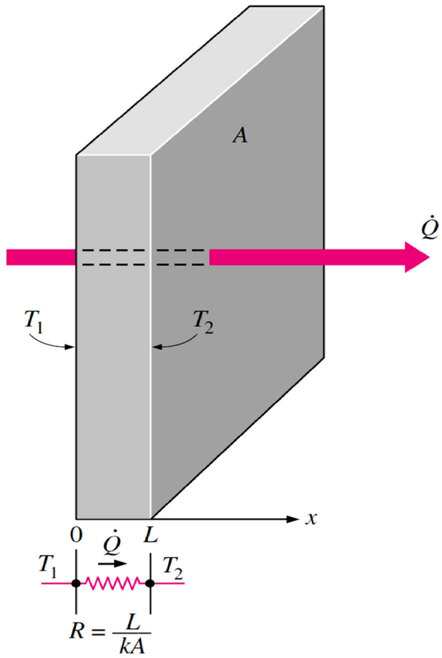


Figure 5.2. Thermal resistance of wall, adapted from [221].

$$\frac{dT_w}{dt} = \frac{Q_s}{C_w} + \frac{T_{out}}{R_w C_w} + \frac{T_{in}}{R_w C_w} - \frac{2T_w}{R_w C_w} \tag{5.9}$$

$$\frac{dT_{in}}{dt} = \frac{(Q_{in} - Q_{ac\_ht})\, S(t)}{C_{in}} - \frac{T_{in}}{C_{in}}\left(\frac{1}{R_w} + \frac{1}{R_c}\right) + \frac{T_w}{R_w C_{in}} + \frac{T_{out}}{R_c C_{in}} \tag{5.10}$$

Table 5.1. Value of thermal constants for a division.

Constant	Value	Units
R_c	3.4294×10^{-6}	(J/K)
R_w	1.5553×10^{-5}	(J/K)
C_{in}	4.43797×10^{3}	(J/K)
C_w	1.64406×10^{4}	(J/K)

5.1.1. Physical Model of Air Conditioning

The air conditioning equipment is specified by its capacity in kW or BTU suits. This capability can be defined as the amount of energy used by the equipment to remove air from the heat and thus regulate the temperature of a room or an entire house. In this work, central air conditioner that divides the configuration using pipelines for cooling one or more divisions is used. This type of air conditioner has a capacity ranging from 9000-60000 BTU [224]. The modeling of the air conditioner can be represented schematically by the heat flow diagram in Figure 5.3. Equation (5.11), presents the Energy Efficiency Ratio (EER) indicates the amount of cooling that is given by the air conditioning, where Q_{out} is the energy required to extract heat from the Q_{in} divisions. Now, W_{in} represents the electrical energy required to complete this work.

$$EER = 3.412 \, \frac{-Q_{in}}{W_{in}} = \frac{Q_{in}}{Q_{in} - Q_{out}} \tag{5.11}$$

5.1.2. Physical Model of Heater

The heater is a cylindrical water tank protected by industrial insulation layer so that it does not quickly cool. This type of system is used more often in countries with a colder climate, having always instant hot water. This type of system can be simulated using the classical thermal model used in [46]. Figure 5.4 shows the circuit used for the water heater, where T_h is the temperature of the water tank, T_{inlet} is the temperature of the water entering the heater and T_{amb} is the ambient temperature around the tank. The density of water is represented by ρ, while the specific heat is represented by C_p. The discharge of water is represented by W_d, which is variable through the day, as will be seen later. Finally, the energy provided to the water to be heated is given by Q_{eg}, η being their respective yields. Equation (5.12) that comes from the work [46], [224], and [219] represents the change of heater temperature for the implemented model in this work:

$$\frac{dT_h}{dt} = \frac{(\rho C_p)W_d}{C_w} T_{inlet} + \frac{UA}{C_w} T_{amb} - \frac{UA + (\rho C_p)W_d}{C_w} T_h + \frac{Q_{eg}\eta}{C_w} \tag{5.12}$$

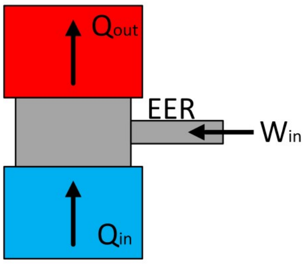


Figure 5.3. Representation of Carnot engine for air conditioning, adapted from [224].

Table 5.2. Value of thermal constants for the heater.

Constant	Value	Units
C_w	7.69910×10^3	(J/K)

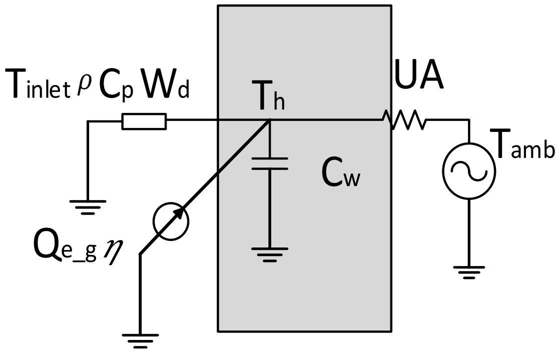


Figure 5.4. Equivalent circuit for the water heater, adapted from [224].

Normally the performance of electric storage water heaters is around 85-94% [224]. Similarly, as done for the physical model of the home to obtain the values of the thermal capacities the electric storage heaters, the equation Equation (5.12) is thereby resulting in the constant Table 5.2.

5.1.3. Physical Model of Refrigerator

The physical model of the refrigerator is modeled in this work as a division of a house in terms of thermal constants, as discussed above. The following Equation (5.13) and Equation (5.14) thus define the physical model of the same charge, result of the constant in Table 5.3 constant [225].

$$\frac{dT_w}{dt} = \frac{T_{amb}}{R_w C_w} + \frac{T_{in}}{R_w C_w} - \frac{2T_w}{R_w C_w} \quad (5.13)$$

$$\frac{dT_{in}}{dt} = \frac{(Q_{in} - Q_{rf})\, S(t)}{C_{in}} - \frac{T_{in}}{C_{in}}\left(\frac{1}{R_w}\right) + \frac{T_w}{R_w C_{in}} + \frac{Q_d}{C_{in}} \quad (5.14)$$

Table 5.3. Value of thermal constants for the fridge.

Constant	Value	Units
R_w	1.5545×10^{-3}	(J/K)
C_{in}	1.4688×10^{3}	(J/K)
C_w	216.6×10^{1}	(J/K)

where T_{amb} is a representation of the temperature within the room, the thermal characteristic of the refrigerator are characterized by R_w as the heat resistance of the walls. In turn, the heat capacity of the walls is represented by C_w and indoor air by C_{in}.

The source that draws heat is identified as Q_{rf} and Q_{in} is the heat to be removed from the refrigerator. S represents a binary variable used for bound states ON (1) and OFF (0). Q_d is the heat transfer to the refrigerator by opening the refrigerator door.

5.1.4. Independent Loads

As indicated above, in this work is considering independent loads as all types of loads in which its use is dependent from the user, and not constantly connected. Within type of loads, it was chosen the following ones: dishwasher, washing machine, tumble dryer and pool pump.

- Dishwasher Machine

The dishwasher has become indispensable equipment in the kitchen over the years. The dishwasher machine is not the equipment that consumes more energy at home, although when used in a short period of time, can reach 1.5kW [226].

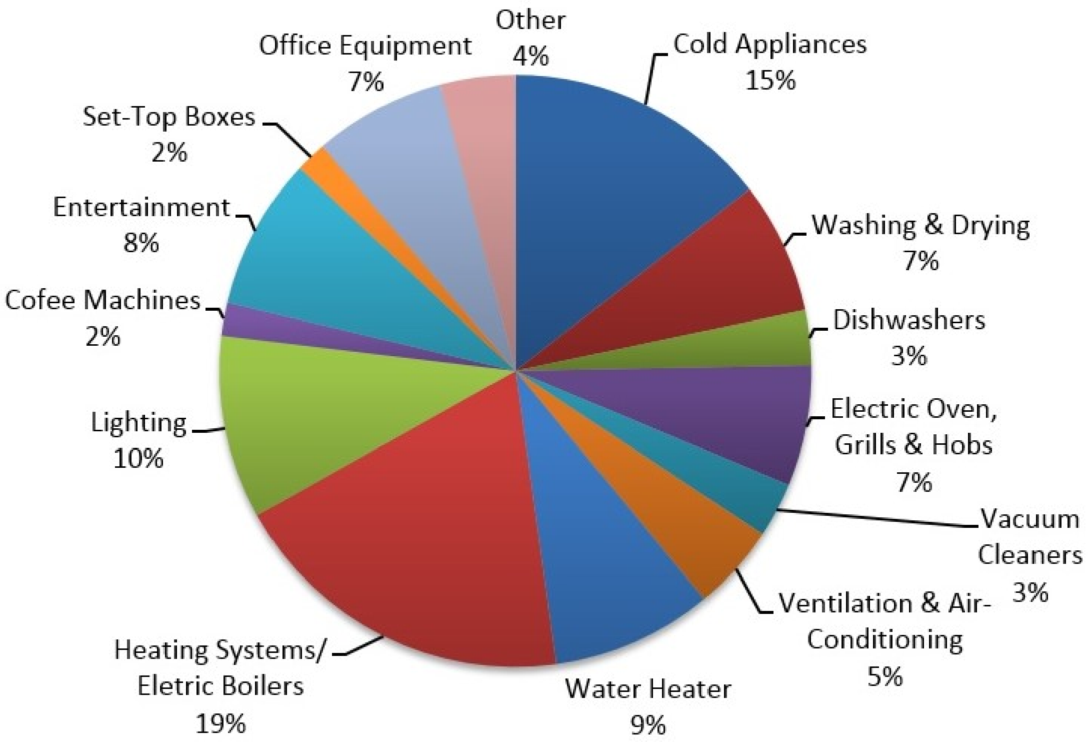


Figure 5.5. Electricity consumption in the residential sector in the EU-27 in 2009, adapted from [231].

- Washing Machine

The washing machine is probably the most used piece of equipment as a whole, since this requires electrical power to be mainly used for rotating the motor and smaller part to heat the water. However, much of the water is used to cool the washing later [227]. This category of equipment usually has a consumption of around 1kW.

Figure 5.5 shows the consumption in terms of percentages of each piece of equipment in the home [228].

- Clothes Dryer

The dryer is mainly used in countries with enough cold climates: in these countries, it is difficult to dry the laundry outside. This type of load consumes large amounts of energy, since generally it has a rated power of 3kW [229].

- The Pool Pump

The pool pump is indispensable equipment in homes where there is a pool to keep the adequate levels of water quality by circulating about 4 - 8hours per day depending of the size of the pool. For this, generally the pump uses a nominal power of 500W. Such pumps are preprogrammed to have ON/OFF programs throughout the day, thus using electromechanical systems for this task is performed [230].

5.1.5. Local Energy Production

Such as referred in previous sections, high consumption of energy is now a reality in developed countries, particularly in Europe. Other forms of energy production for housing consist of photovoltaic panels, or wind turbines that, despite not providing enough power to supply all loads, can partly reduce the purchased electricity from the network. As a result of this, in recent years the use of photovoltaic panels in homes has increased [232]. Since this phenomenon results in part from of government policies to promote such systems, which fight the challenges of demand and promote "clean" energy [233].

Within the day, local generation could possibly satisfy all demand for electricity; but some factors such as wind speed and brightness that cannot change, make the guaranteed electricity insufficient. And this phenomenon of the intermittency nature is one of the great challenges of solar energy and wind energy [234]. The total energy supplied by the sun to the Earth for a day is sufficient for the needs of the same for a year [235]. So, for the installation to be feasible, it is necessary to observe all these variables that relate to the weather, from hours of sun exposure to the annual wind speeds and times of peak consumption, to see if they can make a profit through the investment made.

The work presented in [236] shows the various advantages for the environmental and financial integration of such systems, while the reference [237] analyzed the return times to the investment made regarding installation of the PV. To study the impact of the inclusion of such systems, the deployment of site generation was simulated, as outlined in Figure 5.6 where is described a system of photovoltaic panels installed only for self-consumption *(off-grid)*, with a nominal power of 550W. Thus, the ability to use the energy generated by the residential loads being controlled is simulated.

5.2. Thermostat

Some of the loads described in the previous section, in particular, the air conditioner, refrigerator and the heater are typically controlled by thermostats, since the goal of this type of control is to maintain the temperature of the air or water within preset values also called the comfort range. Figure 5.7 shows schematically the overall operation of the thermostat. Initially there are three air-conditioning loads, the heater and the refrigerator which are subject to external agents (disorders) such as the ambient temperature (T_{amb}), water consumption, among others [224].

Figure 5.7 is described schematically the overall operation of the thermostat. Initially there are three air-conditioning loads, the heater and the refrigerator which are subject to external agents (disorders) such as the ambient temperature (T_{amb}), water consumption, among others. All the loads are controlled by three separate thermostats and as can be seen, each thermostat for different loads sends an ON/OFF signal. However, for this signal to be processed, the thermostat has to take into account four factors; the set-point/reference that the user has set for the system, the temperature of which is what we want to control (T_{in}), the limits to which this temperature operates the upper limit (T_{max}) and the lower limit (T_{min}). These limits set the thermostat hysteresis range, which will be discussed below [224].

Thus, the thermostat is a device that allows the temperature of each load to vary between the upper and lower limit of the desired temperature. Typically, the user has the possibility to adjust this temperature, but in some cases can also control the amplitude of the temperature range. To be able to maintain the ON/OFF switching constantly, the thermostat is equipped with a hysteresis function that is divided into four regions of operation. When the detected temperature reaches a point within the hysteresis band, the resulting state depends on the previous state. Hence, outside the band of the thermostat, the output state is fixed [224].

By other words, when the upper limit is the lower limit has been reached, the output can be configured to turn on the power, in the case of a refrigerator for example. This phenomenon can be seen in Figure 5.8. As time progresses the temperature varies between the two limits defined default charge, or otherwise set by the user.

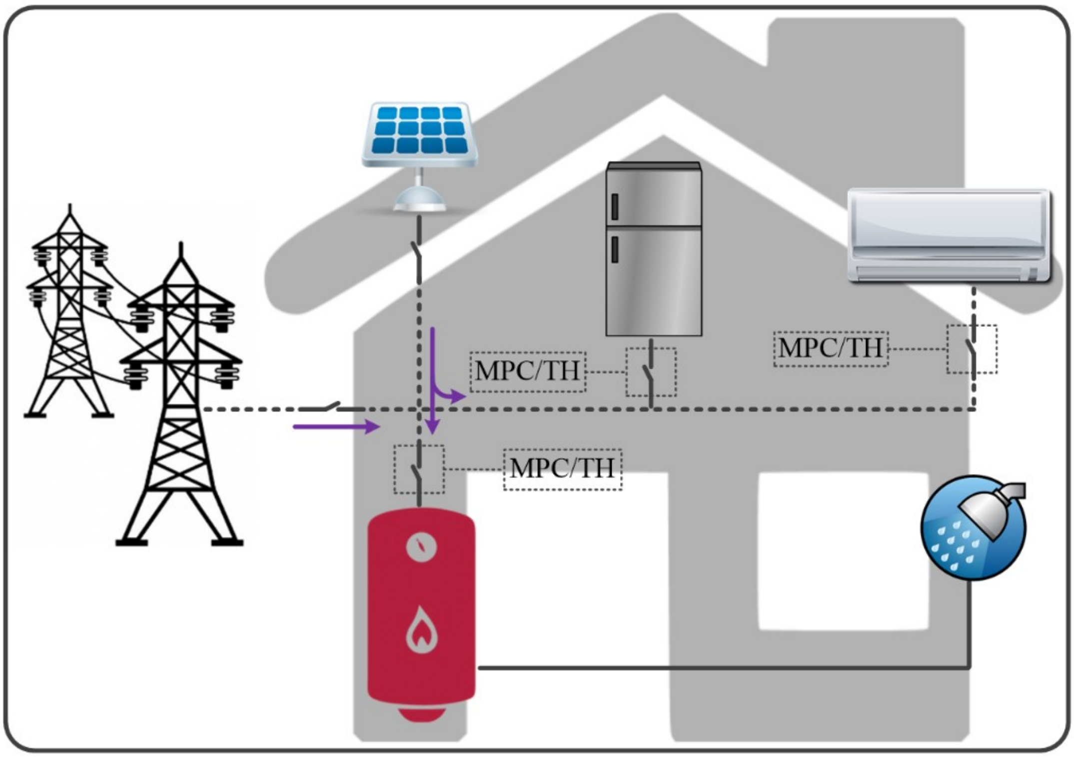


Figure 5.6. Home Power System.

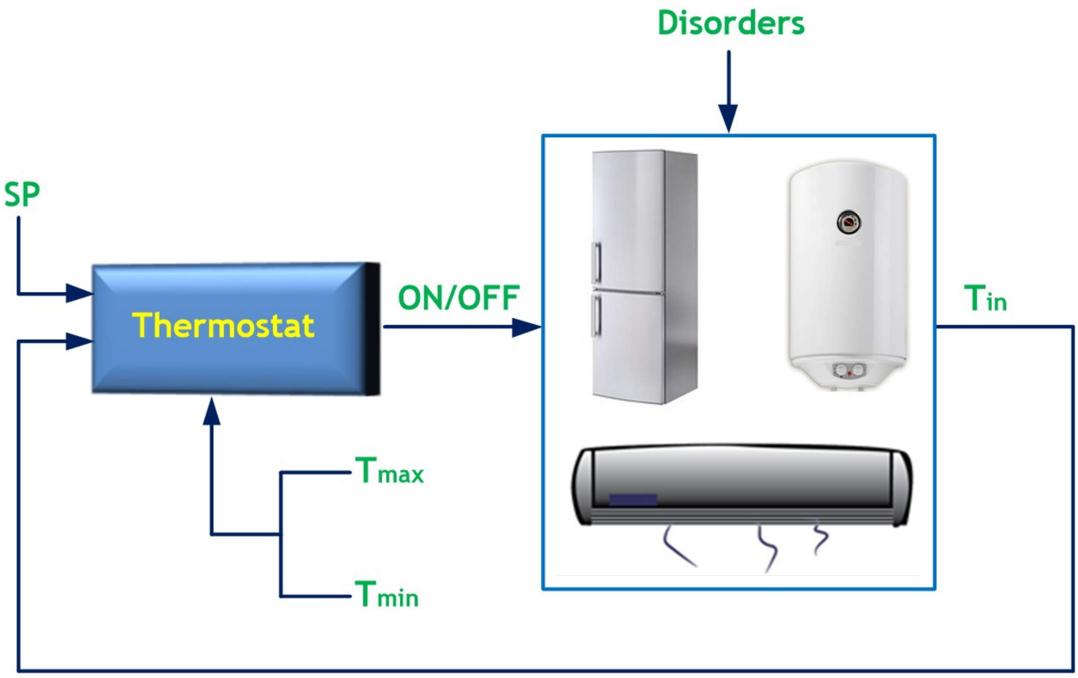


Figure 5.7. Schematic description of the operation and thermostat control strategy.

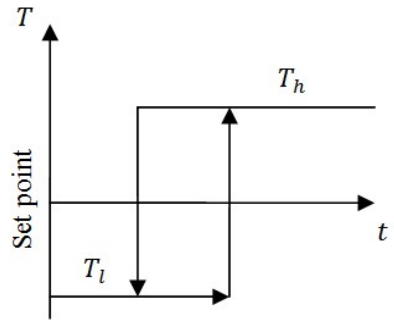


Figure 5.8. Thermostat Operation.

5.3. MPC Control Strategy

The methodology that is characteristic of the MPC family has the strategy exemplified by Figure 5.9, where future outputs are determined according to the prediction horizon, and these outputs provided $y(k+i|k)$ for $i = 1 \ldots P$ depend on the values known at the instant n (i.e. inputs and outputs past) and also of future inputs $u(k+i|k)$, $(i = 0 \ldots P-1)$. In Figure 5.9, past inputs are expressed as a solid line and future inputs are expressed as a broken line. The set of future controls signals is thus calculated by optimizing a given criterion in order to keep the process as close as possible to the reference trajectory (which may itself be the reference or an approximation thereof).

This criterion usually takes the form of a quadratic function of the error between the predicted output signal and the expected trajectory [238]. The control signal $u(k|k)$ (manipulated variables in Figure 5.9) is sent to the process, while the following calculated control signals are rejected because the instant next sample $y(k+1)$ is already known, the process involving the prediction is thus repeated with this new value and all sequences are updated.

Thus, either $u(k+1|k+1)$ is calculated (which will normally be different for $u(k+1|k)$ due to the new information available) using the concept of "receding horizon" [238]. So that the MPC strategy is implemented, its structure is shown in Figure 5.10. Thus, there exists a block that is in charge of providing the model outputs on the basis of input values, which are the current and past values. These actions are calculated by the optimizer, which, in turn, takes into account the cost function, restrictions and future mistakes.

As all simulations were made in Simulink environment, the entire structure MPC shown is based on the block that provides this software, the structure being sketched in Figure 5.11. Normally, this block is used for SISO and MIMO systems.

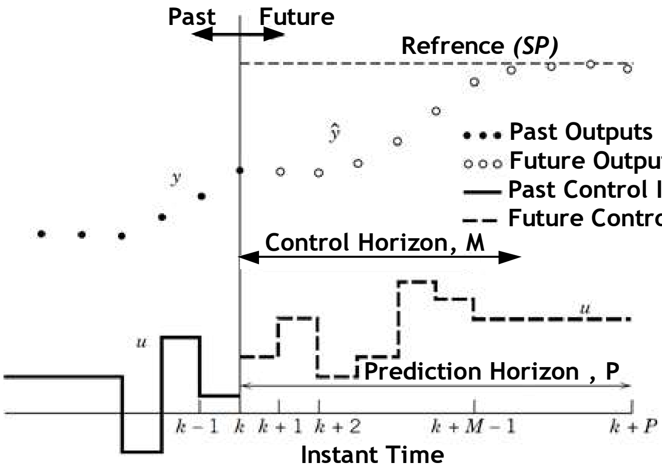


Figure 5.9. Strategy of Prediction, adapted from [239].

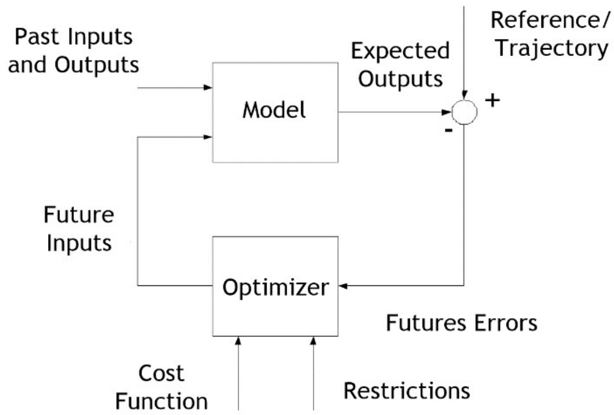


Figure 5.10. Structure of the MPC, adapted from [238].

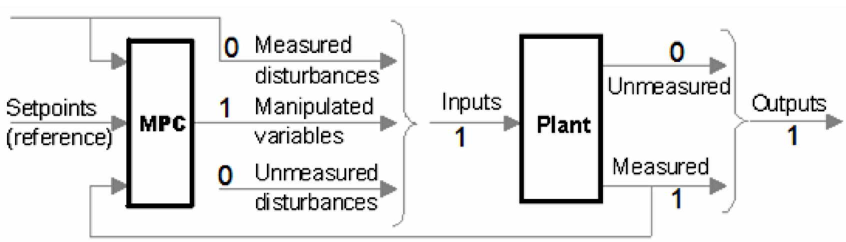


Figure 5.11. MPC control scheme in Simulink.

However, for the case study, the system configures itself according to a SISO scheme (Figure 5.11), because there is only one input and one output, with the input to the controller (MO - Measured Output) to the temperature that one wants to control, either of water or air, and its output (MV - Measured Variables) is a signal that models the power that must be supplied to the system to control the temperature to within the desired parameters. The outputs of the MPC are chosen so that the response prediction has the desired characteristics.

5.4. Optimization Problem

The MPC is an optimization tool used to control different types of processes. Its optimization process produces a sequence of optimal controls according to finite horizon future steps, thus leading to the desired reference systems and at the same time, satisfying all the constraints listed below. The formulation of MPC in the state space equations represents several advantages, from it being easy to represent multivariable systems, to detailed analysis in closed loop.

The system as controlled can be described in the form LTI (Linear Time Invariant) where the Equation (5.15) and Equation (5.16) are: where x is the system state vector, u is the input vector, y is the output vector, A is the state matrix, B is the input matrix, C is the output matrix and D is the feed forward matrix. Given that for a given interval k the model states $x(k)$ are known.

Thus, it is possible to calculate the new input vector to feed the system, taking into account the restrictions [240].

$$x(k+1) = Ax(k) + Bu(k) \tag{5.15}$$

$$y(k) = Cx(k) + Du(k) \tag{5.16}$$

The cost function of the MPC in its standard form can be written as Equation 5.17. This equation results from the sum of three terms, each of which has a different objective to the final result. The priority of each term is defined by the respective weights as discussed below.

Where, z_k is the decision of the Quadratic Program (QP) each control interval, and the solution is used to control MV applied in the system [241]. Equation 5.17 is used to minimize the error that the temperature has in relation to it is reference, i.e., it helps the output of the final temperature to be near or equal to the reference. The second term is related to the violation of the restrictions being used to cushion the restrictions.

Typically, this latter term is used only when there are more OV than MV, this term being equal to zero for this case. The third term is used to control the increments of the *MV*, also called the Rate Weight, because it penalizes the variation of increments instead of the accumulated value. The fourth term is related to the violation of the restrictions. So to be specified Equation 5.17 is obtained by the Equation (5.19) [241].

$$J(z_k) = J_y(z_k) + J_u(z_k) + J_{\Delta u}(z_k) + J_\varepsilon(z_k) \tag{5.17}$$

$$z_k = [\, u(k|k) \;\; u(k+1|k) \; \dots \; u(k+P-1|k) \;\; \varepsilon_k \,] \tag{5.18}$$

$$J(z_k) = \sum_{i=1}^{P} \{\omega^y [r(k+i) - y(k+i)]\}^2 + \\ + \sum_{i=1}^{M} \left\{\omega^{\Delta u} \Delta u(k+i-1)\right\}^2 + \rho_\varepsilon \, \varepsilon_k^2 \tag{5.19}$$

In Equation 5.19, the first term, $y(k+i)$, represents the states of the outputs future, and consequently $r(k+i)$, their respective SP or reference. P is the prediction horizon, and ω^y is responsible for giving the weight more or less importance than the first term. The second term, $\Delta u(k+i-1)$, is defined as the result of future control moves. *M* is the control horizon, and $\omega^{\Delta u}$ is the weight responsible for giving more importance to the second term. Furthermore, the third term ρ_ε is a burden to penalize violations of the restrictions and ε_k is a break variable in the control range k. For values of ω^y greater than $\omega^{\Delta u}$ in the resulting system, the output will be close to the reference, but if the value of ω^y decreases, the difference with the reference system will be higher.

To motivate the driver to use smaller increments in the "MV" the value of $\omega^{\Delta u}$ should be incremented. Thus, the cost function to be minimized has the following restrictions specified by the Equation (5.20) and Equation (5.21) [242].

$$y_{min}(i) - \varepsilon_k V_{min}^{y}(i) \leq y(k+i) \leq y_{max}(i) + \varepsilon_k V_{max}^{y}(i),$$
$$i = 1, 2 \ldots., P \tag{5.20}$$

$$u_{min}(i) - \varepsilon_k V_{min}^{u}(i) \leq u(k+i-1) \leq u_{max}(i) + \varepsilon_k V_{max}^{u}(i),$$
$$i = 1, 2 \ldots., M-1 \tag{5.21}$$

In Equation 5.20, the value of y_{min} and y_{max} represent the lower and upper limits of future output of the system respectively. The parameters V are dimensionless constants of the controller. For large values of V_{min} and V_{max} restrictions are easier to meet. In equation 5.21 the values u_{min} and u_{max} are the lower and upper limit for the MV respectively. The algorithm used by the toolbox MPC uses different ways of solving the problem depending on the presence of restrictions. For the case of no restriction, that is, if all the limits have infinite value then the slack variable is also removed in Equations 5.20 and Equation 5.21 and the problem is solved analytically.

If is not then used one QP to solve the equation. Thus, for this case, the following matrices are used, assuming that $d(k) = n_d(k)$ is a white Gaussian noise, is used Equation (5.22). Therefore, the prediction model are used the Equation (5.23) and Equation (5.24) [242].

$$x \leftarrow \begin{bmatrix} x \\ z_k \end{bmatrix}, \quad A \leftarrow \begin{bmatrix} A & B_k\bar{C} \\ 0 & \bar{A} \end{bmatrix}, \quad B_u \leftarrow \begin{bmatrix} B_u \\ 0 \end{bmatrix}, \quad B_d \leftarrow \begin{bmatrix} B_d\bar{D} \\ \bar{B} \end{bmatrix},$$
$$C \leftarrow [\, C \; D_d\bar{C} \,] \tag{5.22}$$

$$x(k+1) = Ax(k) + B_u u(k) + B_v v(k) + B_d n_d(k) \tag{5.23}$$

$$y(k) = Cx(k) + D_v v(k) + D_d n_d(k) \tag{5.24}$$

For simplicity, in this works is considered the prediction of future trajectories in the model at time $k = 0$, with $n_d(i) = 0$ for all predictions in time it which comes from Equation (5.25) until Equation (5.29) [242].

$$y(i|0) = C\left[A^i x(0) + \sum_{h=0}^{i-1}\left(A^{i-1}B_u\left(u(-1) + \sum_{j=0}^{h} \Delta u(j)\right) + B_v v(h)\right)\right] + D_v v(i) \tag{5.25}$$

$$\begin{bmatrix} y(1) \\ \dots \\ y(p) \end{bmatrix} = S_x x(0) + S_{u1} u(-1) + S_u \begin{bmatrix} \Delta u(0) \\ \dots \\ \Delta u(p-1) \end{bmatrix} + H_v \begin{bmatrix} v(0) \\ \dots \\ v(p) \end{bmatrix} \tag{5.26}$$

$$S_x = \begin{bmatrix} CA \\ CA^2 \\ \dots \\ CA^p \end{bmatrix} \in \mathbb{R}^{pn_y \times n_x}, S_{u1} = \begin{bmatrix} CB_u \\ CB_u + CA\ _u \\ \dots \\ \sum_{h=0}^{p-1} CA^h B_u \end{bmatrix} \in \mathbb{R}^{pn_y \times n_u} \tag{5.27}$$

$$S_u = \begin{bmatrix} CB_u & 0 & \dots & 0 \\ CB_u + CAB_u & CB_u & \dots & 0 \\ \dots & \dots & \dots & \dots \\ \sum_{h=0}^{p-1} CA^h B_u & \sum_{h=0}^{p-2} CA^h B_u & \dots & \sum_{h=0}^{p-1} CA^h B_u \end{bmatrix} \in \mathbb{R}^{pn_y \times n_u} \tag{5.28}$$

$$H_v = \begin{bmatrix} CB_v & D_v & 0 & \dots & 0 \\ CAB_v & CB_v & D_v & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ CA^{p-1}B_v & CA^{p-2}B_v & CA^{p-3}B_v & \dots & D_v \end{bmatrix} \in \mathbb{R}^{pn_y \times (p+1)n_v} \tag{5.29}$$

Considering $[z_0; \dots ; z_{m-1}]$ as the variables in the free optimization problem (for the case of one MV values $\{z_0; \dots ; z_{m-1}\}$ are scalar), the cost function to be optimized is given by the Equation (5.30) until Equation (5.33).

Finally, when substituted $u(k)$, $\Delta u(k)$, $y(k)$, $J(k)$ to the cost function, it can be rewritten by the Equation (5.34), Considering then the limits on inputs, increasing the entrances and exits, along with the constraint $\varepsilon \geq 0$, which is shown in Equation (5.35) [242].

Similarly to what was done with the cost function by replacing $u(k)$, $\Delta u(k)$, $y(k)$ obtained in Equation (5.36), the matrices M_z, M_ε, M_{lim}, M_v, M_u, M_x are obtained by the upper and lower limit. Once the arrays are built the optimization problem is solved at each time interval k [242].

$$J(z,\varepsilon) = \left(\begin{bmatrix} u(0) \\ \dots \\ u(p-1) \end{bmatrix} - \begin{bmatrix} u_{target}(0) \\ \dots \\ u_{target}(p-1) \end{bmatrix} \right)^T + \begin{bmatrix} \Delta u(0) \\ \dots \\ \Delta u(p-1) \end{bmatrix}^T W_{\Delta u}^2 \begin{bmatrix} \Delta u(0) \\ \dots \\ \Delta u(p-1) \end{bmatrix}$$

$$+ \left(\begin{bmatrix} y(1) \\ \dots \\ y(p) \end{bmatrix} - \begin{bmatrix} r(1) \\ \dots \\ r(p) \end{bmatrix} \right)^T W_y^2 \left(\begin{bmatrix} y(1) \\ \dots \\ y(p) \end{bmatrix} - \begin{bmatrix} r(1) \\ \dots \\ r(p) \end{bmatrix} \right) + \rho_\varepsilon \varepsilon^2 \tag{5.30}$$

$$W_u = diag\left(\omega_{0,1}^u, \omega_{0,2}^u, \dots, \omega_{0,n_u}^u, \dots, \omega_{p-1,1}^u, \omega_{p-1,2}^u, \dots, \omega_{p-1,n_u}^u\right) \tag{5.31}$$

$$W_{\Delta u} = diag\left(\omega_{0,1}^{\Delta u}, \omega_{0,2}^{\Delta u}, \dots, \omega_{0,n_u}^{\Delta u}, \dots, \omega_{p-1,1}^{\Delta u}, \omega_{p-1,2}^{\Delta u}, \dots, \omega_{p-1,n_u}^{\Delta u}\right) \tag{5.32}$$

$$W_y = diag\left(\omega_{1,1}^y, \omega_{1,2}^y, \dots, \omega_{1,n_y}^y, \dots, \omega_{p,1}^y, \omega_{p,2}^y, \dots, \omega_{p,n_y}^y\right) \tag{5.33}$$

$$J(z,\varepsilon) = \rho_\varepsilon \varepsilon^2 + z^T K_{\Delta u} z +$$

$$2\left(\begin{bmatrix} r(1) \\ \dots \\ r(p) \end{bmatrix}^T K_r + \begin{bmatrix} v(0) \\ \dots \\ v(p) \end{bmatrix} K_v + u(-1)^T K_u + \begin{bmatrix} u_{target}(0) \\ \dots \\ u_{target}(p-1) \end{bmatrix}^T K_{ut} + x(0)^T K_x \right) z +$$

$$+ \, constant \tag{5.34}$$

$$\begin{bmatrix} y_{min}(1) - \varepsilon V_{min}^y(1) \\ \dots \\ y_{min}(p) - \varepsilon V_{min}^y(p) \\ \Delta u_{min}(0) - \varepsilon V_{min}^{\Delta u}(0) \\ \dots \\ \Delta u_{min}(p-1) - \varepsilon V_{min}^{\Delta u}(p-1) \end{bmatrix} \leq \begin{bmatrix} y(1) \\ \dots \\ y(p) \\ \Delta u(0) \\ \dots \\ \Delta u(p-1) \end{bmatrix} \leq$$

$$\leq \begin{bmatrix} y_{max}(1) + \varepsilon V_{max}^y(1) \\ \dots \\ y_{max}(p) + \varepsilon V_{max}^y(p) \\ \Delta u_{max}(0) + \varepsilon V_{max}^{\Delta u}(0) \\ \dots \\ \Delta u_{max}(p-1) + \varepsilon V_{min}^{\Delta u}(p-1) \end{bmatrix} \tag{5.35}$$

$$M_z z + M_\varepsilon \varepsilon \leq M_{lim} + M_v \begin{bmatrix} v(0) \\ \dots \\ v(p) \end{bmatrix} + M_u u(-1) + M_x x(0) \tag{5.36}$$

In the case the MPC without restrictions, with limits removed, the optimal solution is computed analytically, by the Equation (5.37) and the MPC is defined by the Equation (5.38). In the case of a problem with constraints, the QP solver takes the MPC optimization problem for the general shape of a QP, using the Equation (5.39) as described in [241].

$$z^* = -K_{\Delta u}^{-1} \left(\begin{bmatrix} r(1) \\ \dots \\ r(p) \end{bmatrix}^T K_r + \begin{bmatrix} v(0) \\ \dots \\ v(p) \end{bmatrix} K_v + u(-1)^T K_u + \begin{bmatrix} u_{target}(0) \\ \dots \\ u_{target}(p-1) \end{bmatrix}^T K_{ut} + x(0)^T K_x \right) \tag{5.37}$$

$$\Delta u(k) = z_0^*, u(k) = u(k-1) + \Delta u(k) \tag{5.38}$$

$$Min\left(f^T x + \frac{1}{2} x^T Hz \right) \tag{5.39}$$

In Equation (5.40), where $x^T = [x^T \ \varepsilon]$ are available the decisions, H is the Hessian matrix, A is the matrix of coefficients of linear constraints, f and b are vectors. The matrices H and A are constants.

During startup the controller computes these matrices and recovers them from the saved data when needed. This computes the time variant vector f and b at the beginning of each time control.

This algorithm uses the toolbox KWIK [243], to solve the QP, which requires the Hessian matrix which is positive definite [242].

$$Ax \leq b \tag{5.40}$$

5.5. Control Strategy of the MPC

Figure 5.12 shows schematically the operation of the MPC to control each load. The control principle is similar to the thermostat as depicted above, in this case, there will also be three MPC's, one for each load, with the main function of maintaining the temperature of the air or water near to its reference. As already discussed, the MPC uses various data for this to happen, as the restrictions predictions, the weights, the cost function, among others, as it is these same data that allow the MPC to be so successful [244].

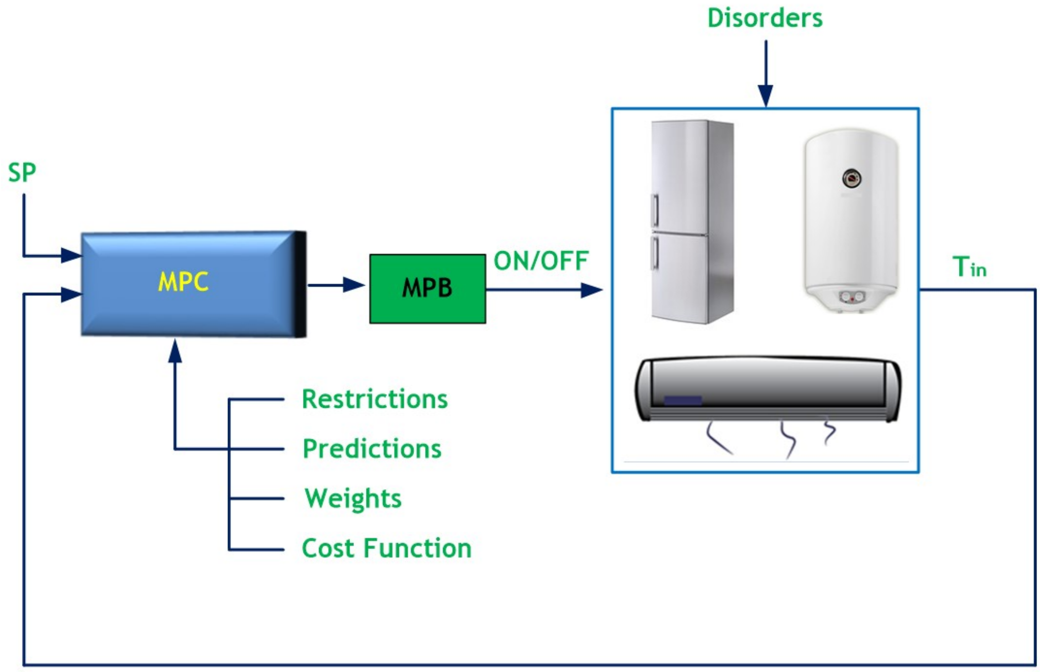


Figure 5.12. Schematic description of the operation and control strategy of the MPC.

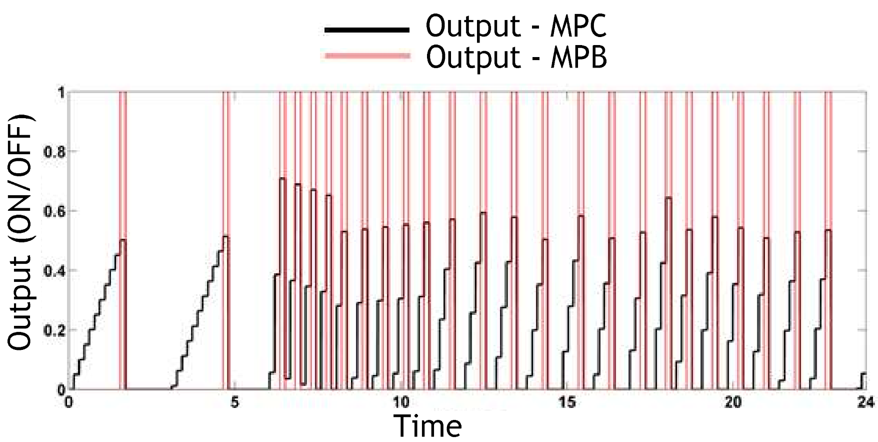


Figure 5.13. Controller output (MPC and MPB), in case of water heater.

Thus, for the MPC to receive the desired temperature value, and taking into account the variables that are provided, such data generates a signaled for the purpose of achieving the reference implemented. This output signal, as shown in Figure 5.12 is then patterned by the MPB (torque power Modeler) block, which works with only two levels either zero or one. This block is critical so that the output becomes solely an ON/OFF signal.

The MPB transforms the output signal from the MPC to the state one or zero, from the charge supply rated power or zero. Furthermore, in Figure 5.12 is shown the layout and operation of the MPC controller together with the MPB. The output signal provided by the MPC so that the temperature is within the desired range is represented in black lines while in red lines is represented the output signal transformed. This block does not translate in full the desired output by the MPC, yet it is through this that it can be left with only two states: ON/OFF. As the MPC, includes the prediction technique, it adapts its output to this block, because even though this output is not that which it provides, the system remains within desired to be analyzed below.

5.6. Cases Studies

5.6.1. Case A: Enhancing Home Appliances Energy Optimization with Solar Power Integration

Case A presents a comparative study between the MPC and Thermostat (TH) approaches to domestic applications with cooling or heating needs specifically Water Heater (WH), refrigerator and room acclimatization by AC. MPC performance is integrated with local power generation and classical control based on thermostatic relay; it is also combined with the local power generation. The objective is to present the difference between these controllers and to observe their effect on local power generation, while satisfying cooling and heating demand and operational load constraints.

The MPC control law is a multivariable control law based on predicted error instead of current control error based correction action. A key aspect of its use is the requirement that a steady state model of the plant is available beforehand.

The MPC operation relies on current measurements and estimation of the future values with regard to the outputs for that model's predictions [245]. The objective is to calculate a sequence of control moves in order to bring the future response to the desired set point in an optimal manner in other words, to perform adequate predictions as close to the specific reference trajectory. A series of control objectives is specified in relation to plant variables and optimized according to the constraints specifications. Let k be the current control instant and $U(k)$ a set of control actions with regards to the next M sampling instants by the Equation (5.41), where $u(k)$ is a current input and $M-1$ future inputs [246].

$$U(k) = [u(k), u(k+1), \dots, u(k+M-1)] \tag{5.41}$$

Hence, $\Delta u(k)$ represents a set of control actions for the next M sampling instants: represents a set of control actions for the next M sampling instants by the Equation (5.42). The MPC control outputs are based on calculating $U(k)$ and $\Delta U(k)$ in way that the predicted outputs achieve the set point in an optimal manner. The number of predictions outputs P is designated as the prediction horizon. Meanwhile, the set of control moves M is referred as control horizon. The control calculations are based on optimizing an objective function, comprising several competing control objectives which are related with process input and output variables [246].

$$\Delta U(k) = [\Delta u(k), \Delta u(k+1), \dots., \Delta u(k+M-1)\,] \tag{5.42}$$

The mathematical form of the cost function is given the Equation (5.43). In Equation (5.44), the term J_y refers to output reference tracking error, where $r(k+i)$ is the desired set-point, $y(k+i)$ refers to the output state while w_i^y establish a weighting factor about this control objective and $k+i$ is the time instant related to the future states prediction [247].

$$J = J_y + J_u + J_{\Delta u} + J_\varepsilon \tag{5.43}$$

$$J_y = \sum_{i=1}^{P} \{w_i^y [r(k+i) - y(k+i)]\}^2 \quad (5.44)$$

The term J_u is the performance index in relation to control move tracking error is given the Equation (5.45), where $u(k+i)$ is the manipulated variable, $u_t(k+i)$ is the desired process input state while the weighting coefficient w_i^t determines the importance of this control objective [247].

$$J_u = \sum_{i=1}^{M} \{w_i^u [u(k+i) - u_t(k+i)]\}^2 \quad (5.45)$$

The term $J_{\Delta u}$ is for imposing gradual changes on manipulated variables. In practice establishes a rate of change of the manipulated variables. The objective function related to this parameter is given by the Equation (5.46), where the input rate of change $u(k+i) - u(k+i-1)$ is penalized by a weighting coefficient $w^{\Delta u}$ and refers to the change in the manipulated input from one sampling instant to the next [248].

In Equation (5.47), the term J_ε is related with the constraint violation used for constraint softening, where ρ_ε is a constraint violation penalty weight and ε_k is a slack variable at sampling instant k.

For values of w^y greater than $w^{\Delta u}$, the plant output will be near the reference, but if the value of w^y is decreased the difference from the reference tracking to the plant output will be bigger.

By the other end to motivate the controller to use smaller increments on the MV the $w^{\Delta u}$ must be increased [249].

$$J_{\Delta u} = \sum_{i=1}^{M} \{w_i^{\Delta u} [u(k+i) - u(k+i-1)]\}^2 \quad (5.46)$$

$$J_\varepsilon = \rho_\varepsilon \varepsilon_k^2 \quad (5.47)$$

Setting constraints on input and output variables is a distinctive feature present in MPC controller design, i.e., the MPC enables the activation of upper and lower limits with regards to the process variables excursion called inequality constraints. Two types of constraints can be defined. The hard constraints for $u(k)$ and $\Delta u(k)$ are specified as upper and lower limits and expressed by the Equation (5.48) and Equation (5.49), while for the outputs, the hard constraints by the Equation (5.50) are computed.

Hence, soft constraints can be used for the optimization problem when hard output constraints are unfeasible solutions using the Equation 5.20 and Equation 5.21 [249].

$$u_{min}(k) \leq u(k+i) \leq u_{max}(k), \qquad i = 0,1 \ldots., M-1 \tag{5.48}$$

$$\Delta u_{min}(k) \leq \Delta u(k+i) \leq \Delta u_{max}(k), \qquad i = 0,1 \ldots., M-1 \tag{5.49}$$

$$y_{min}(k+i) \leq y(k+i) \leq y_{max}(k+1), \qquad i = 1,2 \ldots., P \tag{5.50}$$

5.6.1.1. Results

Power usage and energy consumption depend on how often the appliances are used on a daily basis. In applications with heating/cooling functions, the physical variable under control has a regulation capability associated to the control technique employed. On the contrary, energy costs are indexed to the electricity price structure applied by the energy provider that penalizes the cost of its use for different time periods throughout the day (off-hours, mid-hours and on-peak hours). This section provides a set of results that were obtained to assess MPC capability to reduce energy bills. The comparison is made with the TH. In order to do this, three heating and cooling appliances are used as case studies. The electricity price model is based on the Canadian residential market. Furthermore, to enhance savings on energy bills, an off-grid solar photovoltaic system is integrated into the home power system and its capacity utilization rate analyzed in relation to the settings of the three appliances as a function of the control method. Household power system was presented in previous section in Figure 5.6.

A. Off-Grid Solar Power Generation

The household photovoltaic power system has a rated power of 0.6kW. Figure 5.14 shows the power output profile throughout a 24-hour period. Typically, this profile can help to lower energy costs, since higher generation periods coincide with on-peak hours.

B. Thermostatic Relay

Currently, heating and cooling appliances continue to rely on TH to sense and correct the system's temperature. A TH is a flexible control unit that allows selecting of the lower and higher temperature set points, fixing in this way the temperature band amplitude. Furthermore, the control principle, too, is simple. That is to say, TH operates by switching its output between on and off states. A hysteresis function is also part of the control to avoid switching ON/OFF constantly near the set point.

C. MPC Controller Design and Thermal Models

i) Household Acclimatization

Retention of warm or cold air in a compartment of the house depends on thermal conductivity properties of the physical materials used in its construction. Therefore, energy needs study for room's AC purposes requires the space to be modelled as thermal load to determine the compartment temperature along the T_{amb} acting as the main disturbance source. The equations (5.9) and (5.10) describe the energy flow in a single room obtained from [250]. This case A, Q_{ac_ht} is a thermal source representing the AC device and Q_{ac_ht} is the heat to be removed. A cooling capacity of 8900BTU is used to model AC operation. MPC control range stands at between 22.7ºC and 23.5ºC. In other words, these are the specifications introduced in the controller as output constraints. Consequently, the set point tracking function in relation to a specific temperature is not enabled. The number of M control moves is 2 and the set of P predicted outputs is 10. As for the TH the same operating temperature conditions are chosen. A binary variable S models ON-OFF operation of the AC and TH. For testing and comparing the controller's response the ambient temperature values curve corresponds to a summer day. The values of physical parameters are extracted from [222].

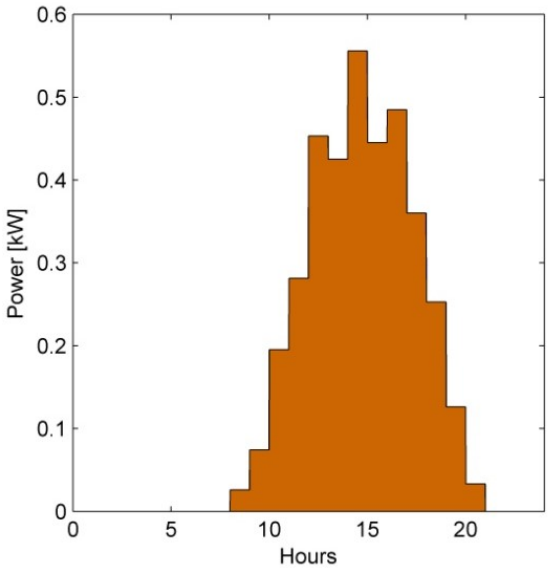


Figure 5.14. Solar Power Generation Curve.

ii) Water heater

Sanitary water heating is common nowadays in any home. A WH is an appliance that provides heat to raise the water temperature inside a tank, in order to be used by the residents in everyday tasks related to personal hygiene.

A typical operation of this device requires the water is warmed up at night when its consumption is minimum. So, the heating time can be extended into the night to take advantage of lower energy costs.

However, at peak times which coincide with the early hours of the morning hot water output has to be compensated quickly. Being a thermodynamic process it is necessary to consider physical parameters such as the mass of water (m), specific heat of water (C_p), fiber glass properties (C_W, UA), gas or electric rated power (Q_{eg}), and the conversion efficiency (η). Energy balance derives from Equation (5.51) [251].

$$\frac{dT_w}{dT} = \frac{mC_P}{C_W} T_{inlet} + \frac{UA}{C_w} T_{amb} - \frac{UA + mC_P}{C_w} T_w + \frac{Q_{eg}\eta}{C_W} \tag{5.51}$$

Tank size of the WH is 184L. Heating process is accomplished through a resistive element rated at 4.5kW. MPC controller is set up to maintain the water temperature between the 53.5ºC and 56.5ºC. The same band tolerance is adjusted for TH operation. Finally, the external temperature surrounding the water tank remains stable at 23ºC. The set of P predicted outputs is 10 and the number of M control moves is 2.

iii) Refrigerator

It is one of the few appliances that require to be continued connected to the mains power source in order to keep food in optimal conditions of preservation. Its thermal behaviour can be approximated with the Equation (5.9) and Equation (5.10). However, contrary to WT the refrigerator is covered with fiber glass in order to minimize heat absorption coming from the surrounding environment, giving it the characteristics of an isolated thermal system.

But whenever the refrigerator's door is open low temperature condition is disturbed. Therefore, the number of openings will impact the additional energy requirements to re-establish the normal operating conditions. Refrigerator compressor motor is modelled with a power rating of 230W and MPC range control is defined with a lower limit of 3.9ºC and upper limit of 5.1ºC. For disturbing refrigerator working conditions two door opening closing sequences are generated at 10:00–11:00 pm and at 14:00–15:00pm respectively. M control moves number is 2 and 10 is the set of P predicted outputs.

iv) TH vs. MPC Without Solar Power Generation

Simulation results concerning controller's response for the three appliances are depicted in Figure 5.15, Figure 5.16 and Figure 5.17, respectively. Room's temperature curve seems to be very similar for both controllers when observed from tolerance specification view point. It can be seen the MPC does not to reach the upper and lower limits to perform the regulation.

In the water heating application when there is a surge of water consumption MPC initial response is worse. However, after this moment, temperature excursion remains within the regulation limits. It is clear in Figure 5.17 that MPC handles in a less effective way the disturbances.

Indeed, in the second event of disturbance the temperature raises almost 1ºC. Controller's performance with regards to each time period of the day is evaluated in terms of energy required to perform the cooling and heating tasks as whole, along with their respective electricity costs, as shown in Table 5.4.

As can be seen MPC achieves with a slightly higher performance than the thermostatic relay. Total energy consumption is reduced in 250W which involves a quantifiable saving of 0.05$. In others words, energy bill suffers a contraction of 1.27% which is significant.

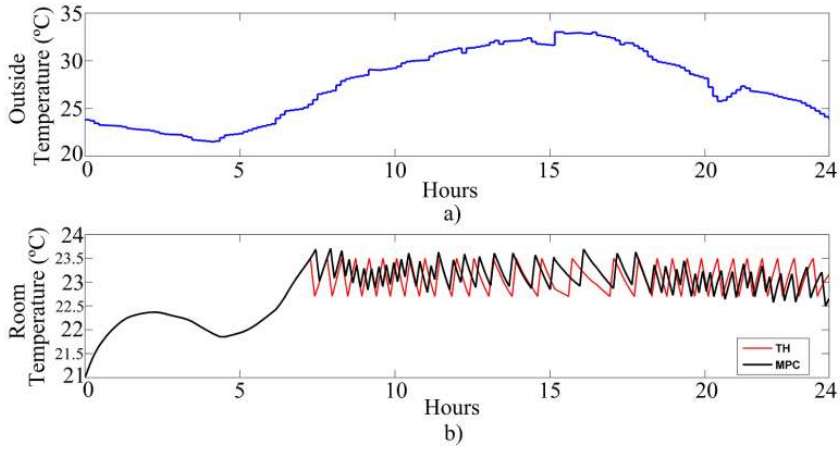


Figure 5.15. Household: a) T_{amb} profile; b) TH vs MPC.

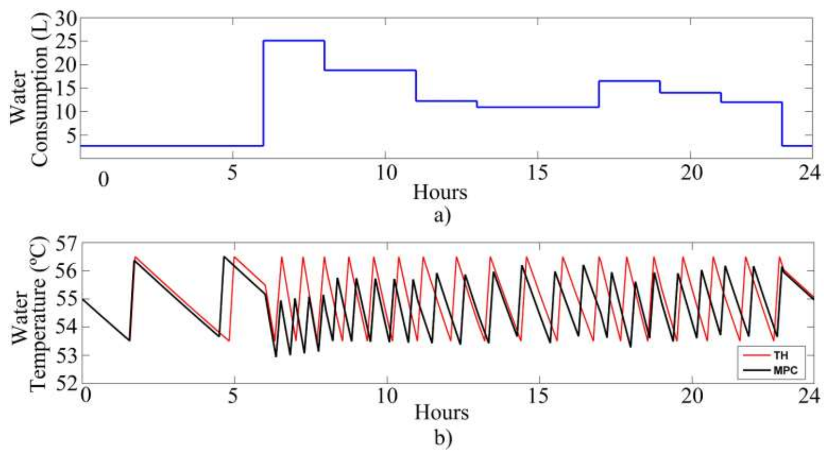


Figure 5.16. Water heater: a) Water Consumption profile; b) TH vs MPC.

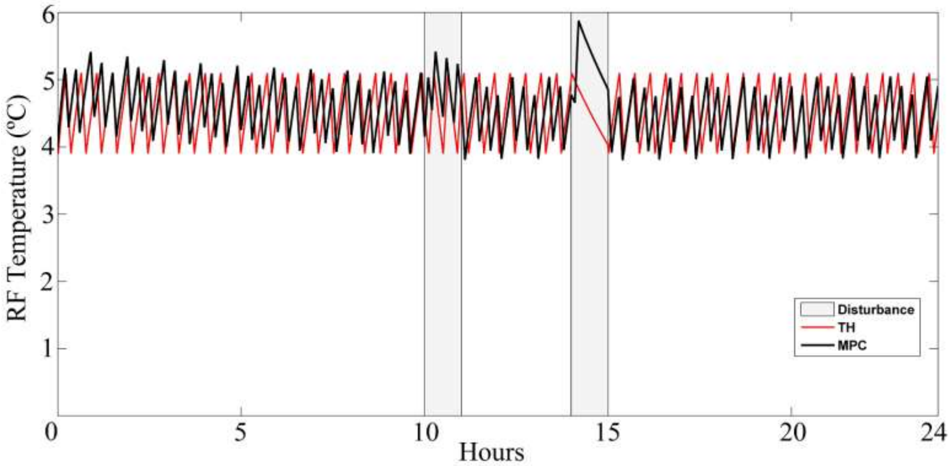


Figure 5.17. Refrigerator: TH vs. MPC.

Table 5.4. Energy Consumed VS Energy Cost.

	Thermostat		MPC	
	Energy (kWh)	**Cost ($)**	**Energy (kWh)**	**Cost ($)**
Air conditioner	26.356	2.482	26.272	2.468
Water heater	17.598	1.520	17.437	1.483
Refrigerator	1.878	0.157	1.863	0.155
Total	45.832	4.159	45.572	4.106

v) TH vs. MPC with Solar Power Generation

With home photovoltaic power installation enabled power output is available to supply to the three appliances. As such, Solar Capacity Utilization Rate (SCUR) is measured taking into account the control methods under study. For that purpose, Figure 5.18 highlights at black trace every moment when solar energy is not consumed by the appliances controlled with TH.

Despite the solar power generation peak can be considerable lower than the rated power of the appliances, it is not possible to make a complete use of the energy coming from the solar installation. This can be explained with the fact that the appliances involved in this study have different power needs during the day. In turn, their demand is also different to each other. Meanwhile, solar power integration is less effective when TH controller is replaced by the MPC. In Figure 5.19 can be observed that most solar power generation curve is affected. Naturally this is a confirmation of better energy usage by the MPC.

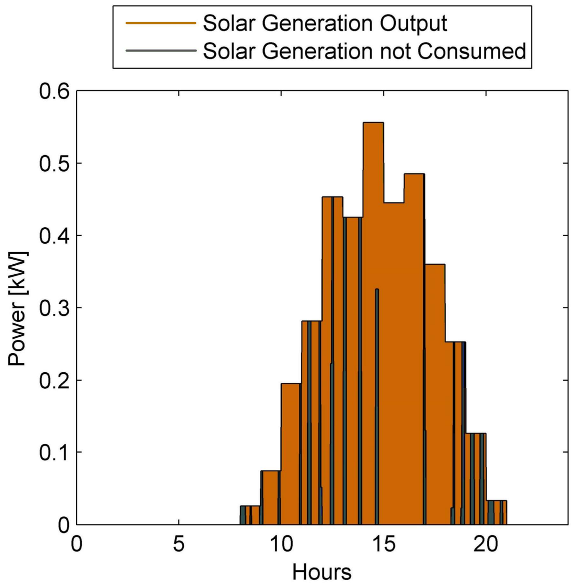


Figure 5.18. Solar Energy Absorbed by appliances controlled by TH.

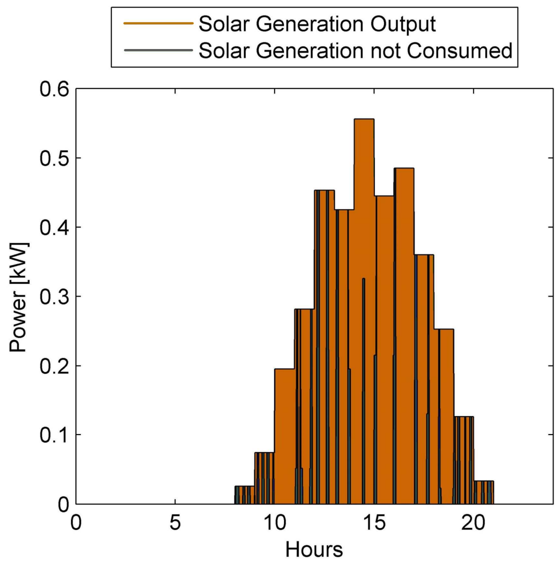


Figure 5.19. Solar Energy Absorbed by appliances controlled by MPC.

Thus, solar energy not consumed will grow. SCUR numbers and impact on energy bills are presented in Table 5.5. In the case of using TH solar energy wasted is 12.451% (0.4625kW). Combining the renewable production with MPC controlled appliances the energy not used goes up to 14.125% (0.525kW). Finally, it can also be seen the impact on the electricity bill reduction.

Table 5.5. Energy Consumed VS Energy Cost with Solar Power Integration.

	Thermostat		MPC	
	Energy (kWh)	**Cost ($)**	**Energy (kWh)**	**Cost ($)**
Off-peak	11.648	0.722	12.065	0.748
Mid-peak	14.853	1.366	15.222	1.400
On-peak	16.079	1.736	15.096	1.630
Total	42.579	3.825	42.383	3.779
	SCUR (%)	**Bill reduction (%)**	**SCUR (%)**	**Bill reduction (%)**
	87.549%	8.03%	85.875%	9.14%

The value for each case was obtained using as reference the energy total cost with thermostatic control and without solar power integration from Table 5.4.

5.6.2. Case B: Model Predictive Control Technique for energy Optimization in Residential Appliances

Case B presents MPC approach to domestic applications with cooling or heating needs, namely Water Heating (WH), room acclimatization by Air Conditioner (AC) and refrigerator. MPC performance is compared to traditional control based on thermostatic relay.

The objective is to present a predictive controller that minimizes energy consumption while satisfying cooling and heating demands and operational constraints of loads. For simulation purpose, domestic load models have been created to represent their dynamic characteristics, which enable to characterization of MPC and TH controllers' response.

A. Household

Building material properties dictate thermal response and consequently the energy consumption behavior. Thus, retention of warm/cold air in the house depends on thermal conductivity characteristics of the materials used on the floor, roof, windows and walls. As a whole, thermal performance is defined by the house geometry and the number of rooms.

In this case study, three rooms are modeled, while only one is equipped with a temperature regulation system. Single room dynamic model takes into account the outside environment, T_{amb}, and the thermal characteristics of the room.

The AC power unit is represented as Q_{ac_ht} thermal source, while the heat to be extracted is represented as Q_{in} thermal source. A binary variable S models ON-OFF operation of the AC/TH. Thermal equations are derived from [250] as:

$$\frac{dT_{in}}{dt} = \frac{(Q_{in} - Q_{ac_{ht}})S(t)}{C_{in}} - \frac{T_{in}}{C_{in}}\left(\frac{1}{R_w} + \frac{1}{R_c}\right) - \frac{T_w}{R_w C_{in}} \tag{5.52}$$

B. Water Heater

Physical description model of the WH takes into account the mass of water (m), specific heat of water (C_p), characteristics of fiber glass $(C_w,\ UA)$, gas or electric rated power (W_{eg}), and the efficiency (η). Energy transit equation for WT has the following expression [251]:

$$\frac{dT_w}{dt} = \frac{mC_P}{C_W}T_{inlet} + \frac{UA}{C_w}T_{amb} - \frac{UA + mC_P}{C_w} + Q_{eg}\eta \tag{5.53}$$

C. Air Conditioner

The AC unit model is represented by an input-output power block that receives a certain amount of energy Q_{out} (cooling capacity in terms of BTU) to remove heat Q_{in} from the air inside the room. In the model, AC energy efficiency is equal to one.

D. Refrigerator

The fridge unit is modeled as an isolated thermal system coated with fiber glass. The dynamic response can be described by the room model equations previously introduced with adjustments on model parameter values.

E. MPC

The MPC is essentially an optimization tool to solve a series of control objectives formulated over a finite prediction horizon. This means the optimization process produces a sequence of optimal control actions driving the system output towards a known reference, and at the same time satisfying system constraints and minimizing a specified performance criterion.

MPC implementation requires previous model knowledge of the plant to predict and optimize future states. In this regard the system to be controlled can be described by LTI equations as a discrete-time state space model, using the Equation (5.15) and Equation (5.16).

Furthermore, the main function MPC can be written by the Equation (5.54) and Equation (5.55), where $r(k+i)$ are the future output states and $y(k+i)$ is the respective set point, P is the prediction horizon and M is the control horizon, $\Delta u(k+i-1)$ is the future sequence of control moves, ω^y and $\omega^{\Delta u}$ are weighting values in which the first term is used to minimize reference temperature error, while the second term penalizes changes in the control input. For case study B, the goal is the future output for the considered time horizon should tracking the temperature SP with minimum control moves to accomplish the goal of energy consumption minimization [251].

$$J = \sum_{i=1}^{P} \{\omega^y [r(k+i) - y(k+i)]\}^2 + \sum_{i=1}^{M} \left\{\omega^{\Delta u} \Delta u(k+i-1)\right\}^2 \tag{5.54}$$

$$r_{min}(i) \leq r(k+i) \leq r_{max}(i) \tag{5.55}$$

F. Thermostat

The TH is a device that allows the system temperature to oscillate between upper and lower temperature limits. Normally the user has the possibility to adjust the desired temperature and in some cases the temperature band amplitude as well. To keep switching ON-OFF constantly, a thermostat is equipped with a hysteresis function that divides TH operation in four regions.

When the sensed temperature falls at a point inside hysteresis band values, the present state depends on the previous state, as can be seen in Figure 5.8 of previous subsection. Hence, outside of the band TH the output state is fixed. To sum up, when the upper limit is reached the output state can be configured to switch ON the power, for example. Whereas, at the other extreme limit, output state switch OFF the power. So as time goes forward the temperature varies between the two limits close to the set point defined by the user.

5.6.2.1. Results

This section is dedicated to presenting the main results, having as it is scenario the prices charged for the residential market in Canada. The daily electricity fee is structured on three price levels according to different demand periods, assigned as off-hours, mid-hours and on-peak hours. WT, refrigerator and room's temperature equation models are simulated to recreate a 24-hour time period. For each physical model, the two control methods (TH and MPC) are compared based on the power consumption and the corresponding cost of consumed energy.

A. Household

A small AC unit with 8900 BTU is used to cool the three room's residency. The AC operation is controlled externally by a temperature control system, which comprises a temperature sensing device and a decision unit based on a control action.

Both controllers are adjusted to a temperature reference of 23ºC. The TH is set with a +/- 1º tolerance band, while in MPC takes a form of sensed temperature restriction between 22.5ºC and 23.5ºC.

Data collection reports to room's AC power consumption, room temperature and outdoor temperature, which account as disturbance source of the system. An outdoor temperature profile is generated recreating a hot summer day. Considerable thermal amplitude is introduced to work as a disturbance source on the room's temperature equation model. AC outputs with TH and MPC controllers are shown in Figure 5.20 and Figure 5.21, respectively.

Room’s temperature curve seems very similar for both controllers when observed from tolerance specification view point. A further analysis indicates that with TH control the average temperature is 23ºC because the temperature variation does not break the upper and lower limit of hysteresis.

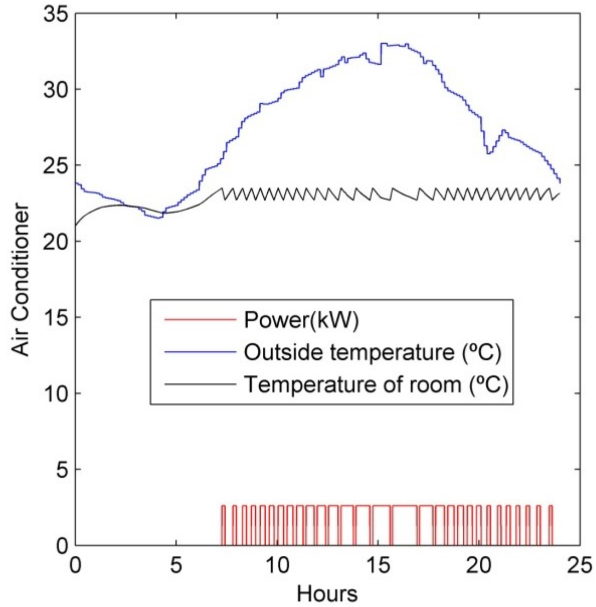


Figure 5.20. Air Conditioner with thermostatic Control.

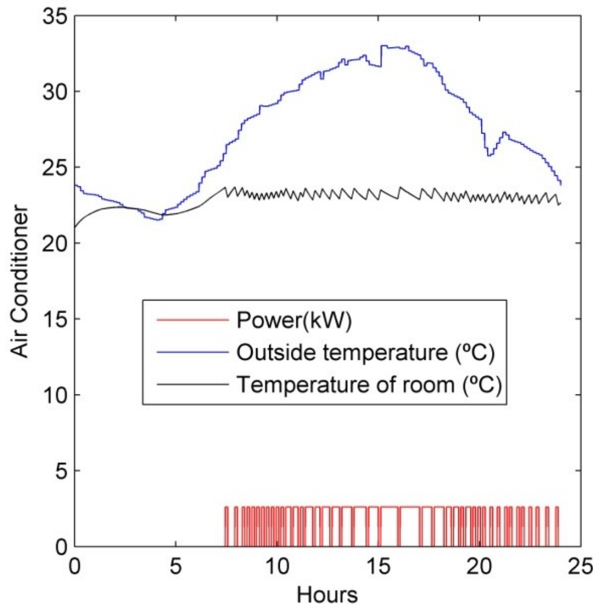


Figure 5.21. Air Conditioner with MPC.

Table 5.6. Air Conditioner: energy cost vs. control method

	Thermostat		MPC	
	Energy (kWh)	**Cost (€)**	**Energy (kWh)**	**Cost (€)**
Off-peak	5.005	0.310	5.065	0.314
Mid-peak	8.417	0.774	8.546	0.786
On-peak	12.934	1.397	12.661	1.367
Total	26.356	2.482	26.772	2.468

As for the control via MPC, the average temperature is somewhat lower than 23ºC, varying slightly with MPC actuation. Nevertheless, it fulfills easily the temperature specification. In sum, MPC does not to reach the upper and lower limits to perform the regulation. At this point, effectiveness of the controllers is measured by comparing consumed energy and the electricity bill that guarantee room's temperature requirement. The economic figures are given in Table 5.6; it is possible to see that the MPC strategy is less demanding in energy terms.

For this outcome, MPC performance is decisive during on-peak hours, with the highest electricity unit cost with outdoor temperature approaching the peak. As a result, a global lower cost is achieved with the MPC strategy, which is noteworthy.

B. Water Heater

A WH device has a usage pattern related to house resident's daily hygiene since it works as a hot water tank. Thus, it is expected that during night the water has to be warmed up at a slower rate, while at peak-hour the temperature control system must react fast enough to compensate hot water out. A rated 4.5kW resistive element is used for water heating. In terms of tank net volume, the storage capacity is 184 L. MPC and TH are initialized with similar requirements. That is, the SP is 55 ºC with a +/-1.5 ºC band as tolerance for TH, while MPC input is fed with the allowable temperature range as a control constraint variable.

WT outside air temperature is fixed at 23 ºC. Figure 5.22 shows the simulation of the WH system controlled by thermostat, followed by Figure 5.23 related to MPC actuation. For the same consumption profile, independent of the control solution, the water temperature inside the tank is within the tolerance limits of the process.

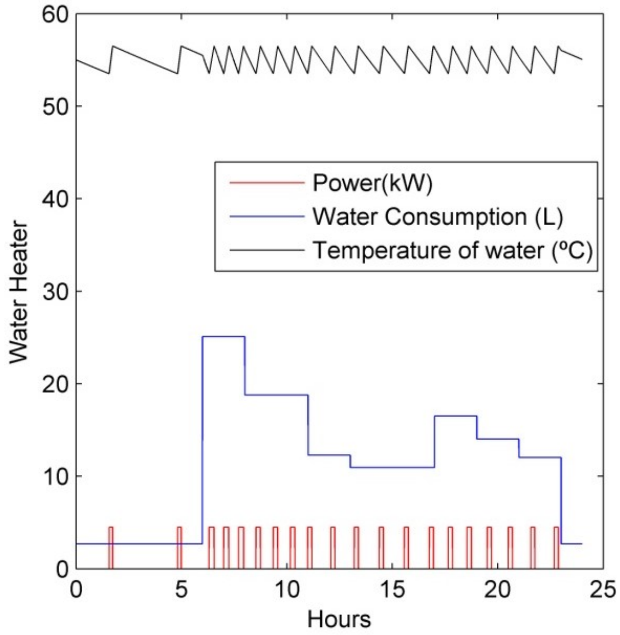


Figure 5.22. Water heater with thermostat Control.

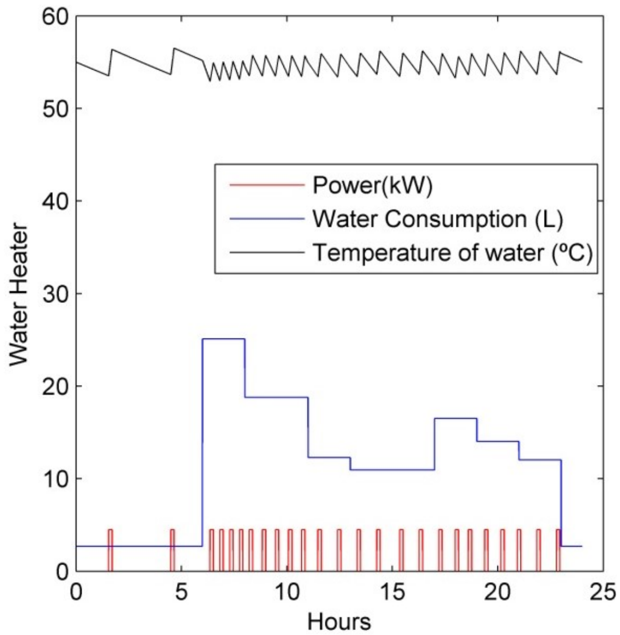


Figure 5.23. Water heater with MPC.

Table 5.7. Water Heater: energy cost vs. control method.

	Thermostat		MPC	
	Energy (kWh)	**Cost(€)**	**Energy (kWh)**	**Cost(€)**
Off-peak	5.919	0.367	6.278	0.389
Mid-peak	6.740	0.620	6.975	0.642
On-peak	4.939	0.533	4.185	0.452
Total	17.598	1.520	17.437	1.483

Continuing the trend observed in the previous example, water temperature regulation under MPC supervision shows a more moderate variation at the beginning of peak-hour, which can indicate an increased energy usage. To confirm it, Table 5.7 presents the consumption in each gap (off-peak, mid-peak, on-peak) and the respective cost for the control with TH and MPC. Here again, on-peak hours cost puts the MPC to exceed TH performance. Note that the largest fraction of water consumed resides away from peak hours, revealing that MPC can handle better the cost factor. A positive outcome is the fact that total cost savings achieved on this application is higher, again noteworthy.

C. Refrigerator

Typically, a refrigerator is a household appliance very sensitive to the external temperature. Therefore, the time number the refrigerator's door is opened or kept open, forces the thermal control to take action. A simple test is performed considering a unit with a power rating of 0.23kW. SP for thermostat action is 4.5ºC plus +/-0.6ºC of tolerance.

An equal temperature range located between 3.9ºC and 4.6ºC is loaded on the MPC program. Here the evaluation consists in retaining the refrigerator's door open, first for 10 minutes at 10:00pm and later for 1 hour at 14:00 -15:00pm. TH and MPC specific responses are shown in Figure 5.24 and Figure 5.25, respectively. It is clear from the TH plot that disturbances are handled, the only issue being time. In fact, when for the second time the door is opened, TH forces the refrigerator compressor to operate for almost one hour trying to reach the TH lower limit. However, MPC is set with a specific sample rate to update model states and to generate an output state. In this particular simulation, the updating rate occurs at six minute intervals.

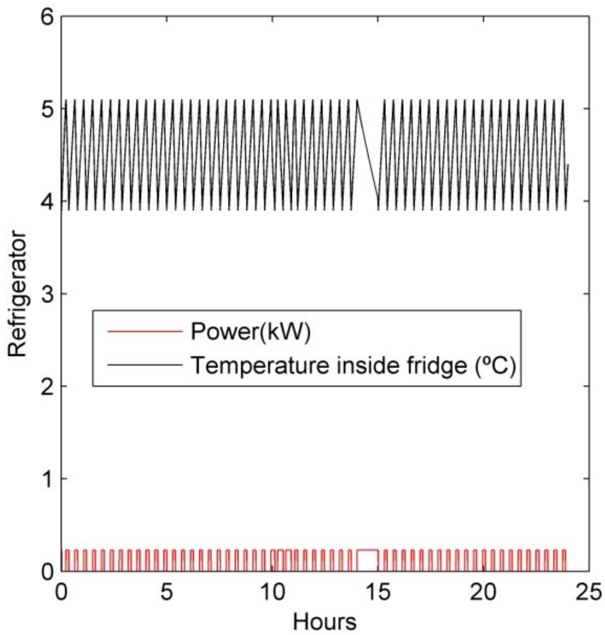


Figure 5.24. Refrigerator with thermostatic control.

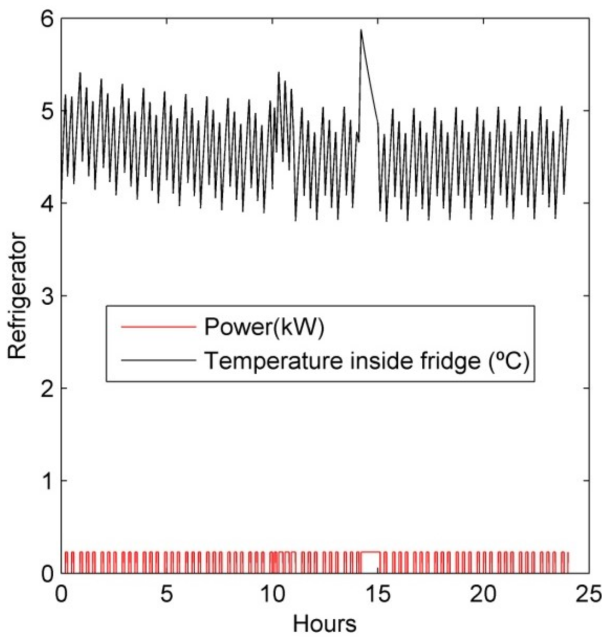


Figure 5.25. Refrigerator with MPC.

Table 5.8. Refrigerator: energy cost vs. control method.

	Thermostat		MPC	
	Energy (kWh)	**Cost(€)**	**Energy (kWh)**	**Cost(€)**
Off-peak	0.824	0.051	0.828	0.051
Mid-peak	0.504	0.046	0.483	0.044
On-peak	0.549	0.059	0.552	0.060
Total	1.878	0.157	1.863	0.155

Having this in mind, MPC response comes a bit late, allowing the temperature to climb up to 6ºC. This is not a problem, because the peak of temperature is still inside the usual temperature ranges found in domestic refrigerators. Returning to the first event, MPC doesn't seem to absorb well the disturbance impact, even on a smaller scale. Hence, it is necessary to shorten the sample rate time interval. From the economic comparison provided in Table 5.8, MPC adaptation as a control solution does not offer a significant advantage here. However, further investigation has to be made.

D. Overall economic analysis

The information previously collected is reorganized in order to disclose potential savings on the electricity bill due to the control method adopted. Table 5.9 presents overall saving figures for each of the domestic applications simulated. It can be seen that in all domestic applications the MPC technique allows a reduction on daily energy costs. The water tank appliance stands out with the best result. Combining the three residential appliances, the resulting amount allows an energy bill reduction of 1.27%.

Table 5.9. Cost Savings vs. control method.

Appliance	Thermostat	MPC	Cost Savings (%)
	Energy (kWh)	**Energy (kWh)**	
Air Conditioner	26.356	26.272	0.56
Water Heater	17.598	17.437	2.47
Refrigerator	1.878	1.863	0.89

5.7. Demand Management

This subsection describes demand management, which is only a superficial assessment of what can be done about this issue. To study the effects of demand management, it is considered just like loads the washing machine, dishwasher, dryer and even the pool pump. These have the advantage that it may be connected at any time of day.

In Figure 5.26 shows a result from Matlab simulations of a possible scenario existing in a house. The loads are all connected for an hour except the pool pump, which has in this case a continuous operation of 5 hours. The blue curve corresponds to the energy consumed. In Table 5.10 shows the hours when the aforementioned consumptions happen allowing the improvements. From Table 5.10, we can see that much of the consumption takes place in mid-time and on-peak, which inevitably leads to higher costs.

When the loads of these hours for the empty hours we can see from in Figure 5.27 that the charges were all displaced to-peak hours, confirming the information in Table 5.11.

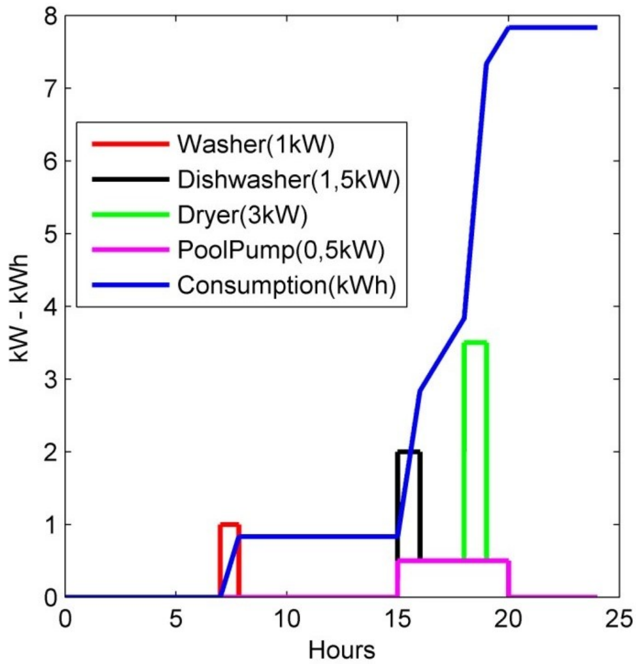


Figure 5.26. Typical scenario residential consumption.

Table 5.10. Typical residential consumption.

Consumption	Energy (KWh)	Cost ($)
Off-peak	0.500	0.031
Mid-peak	4.833	0.445
On-peak	2.500	0.270
Total	7.833	0.746

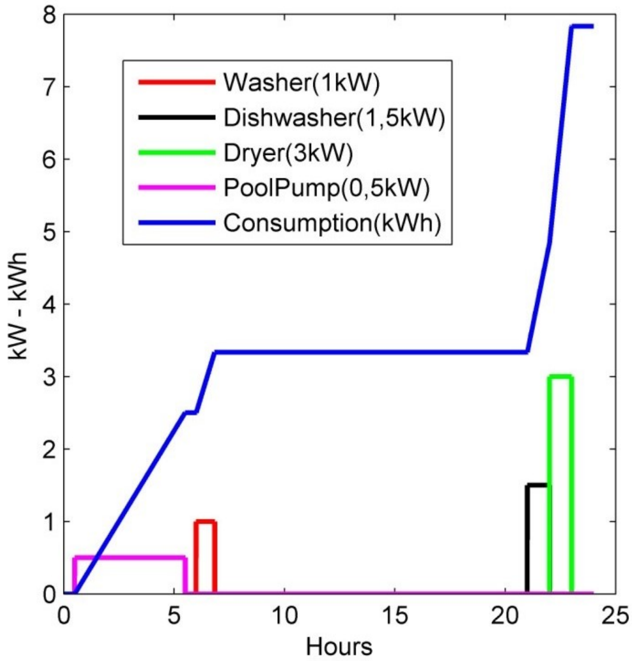


Figure 5.27. Possible scenario residential deployment.

Table 5.11. Possible residential consumption.

Consumption	Energy (KWh)	Cost ($)
Off-peak	7.833	0.486
Mid-peak	0	0
On-peak	0	0
Total	7.833	0.486

Thus, despite the energy consumed being the same, the cost was reduced by approximately 35%.

In many homes today, this technique of load shifting is already done by programmable devices in the pool pump that can be turned on and off several times, and the washing machines and dryers. Load shifting, means a good reduction of the final cost and, at the same time helps reduce the stress on the network at mid-times and peak-times. The ultimate goal of this type of demand management is that there is an interaction between all of these devices, and they can automatically turn ON and OFF.

5.8. Scenarios Forecast for the Residential Sector

According to the previous section, the hours for moving these loads in the underlying model are, between 7:00pm and 6:00am the next day. So, was simulated in Matlab another program to realize the effects on consumption and stress on the network. For this purpose, the program calculates multiple deployment scenarios in several rooms simultaneously, where there are the following restrictions:

- In all scenarios, all equipment is connected in the rooms over this period; Loads all have the duration of one hour, since they were not repeated in the same house;
- The variation in consumption over this period must be as short as possible to avoid fluctuations and thus the request to the network is relatively constant, thus reducing also the stress within hours.

For implementation in a building with eight apartments, 100,000 possible cases are simulated, the result is shown in Figure 5.28.

Through the analysis of various scenarios, the program collects one lower standard deviation, in this case 0.537. In the first hour is possible to see the effect of programming for 20 and 21 hours' consumption will be the same: each housing uses the dryer between, 20:00h and 21:00h, there are two housing that uses the dishwasher. To make the standard deviation lower still and to add another load, the pool pump is considered. This has the great advantage of being able to allocate a site to try to keep the various loads constant, being possible because of its easy and low rated power.

Thus, for the same number of simulations, (100,000), and the same number of eight apartments, all the system is added to the pool pump, which is shown in Figure 5.29.

In this case, the standard deviation is 0.597, which, although larger, can be seen in Figure 5.29 to have had the desired effect because the pool pump was connected to 22:00h, 1:00h and 2:00h, therefore increased consumption at these times and helped to balance the average.

The only point that could be optimal at 4h as the maximum power consumption is to be increased, which is not desirable at all. To test the effects on a larger scale, Figure 5.30 shows the results for a simulation of 100,000 cases, but for 20 houses.

In detail, Figure 5.30 shows, for 20 houses, a standard deviation of 0.916, which is higher than the former, because in this situation there are more houses and a number of increased possibilities, so that the variance has increased.

With the pool pump, Figure 5.31 shows a decrease in standard deviation to 0.821. It is evident that the pump helps to balance consumption, making it more constant, again excepting the case in which it is allocated again at the time of higher consumption.

However, this decrease can also be explained by the fact that the number of simulations has been increased to 150,000, because the standard deviation is still high compared to the results for 8 houses.

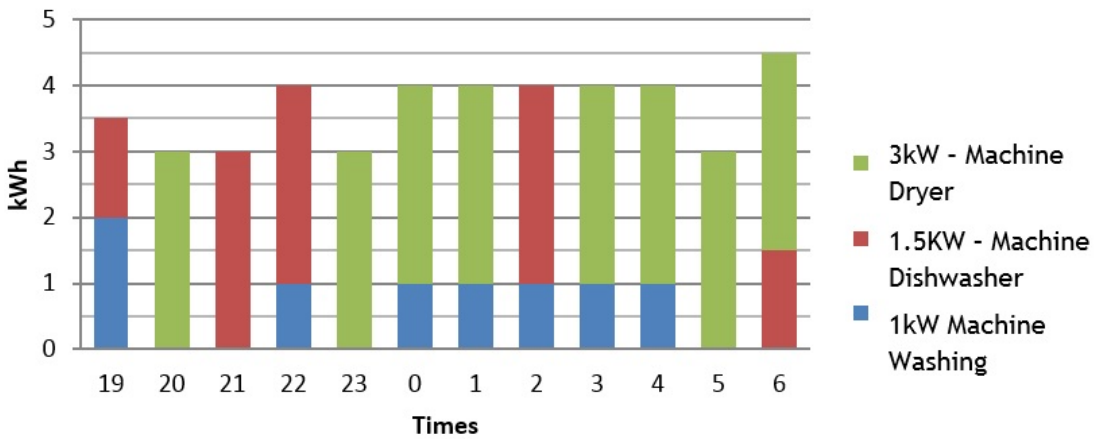


Figure 5.28. Scenario 1: Distribution of consumption 8 housing.

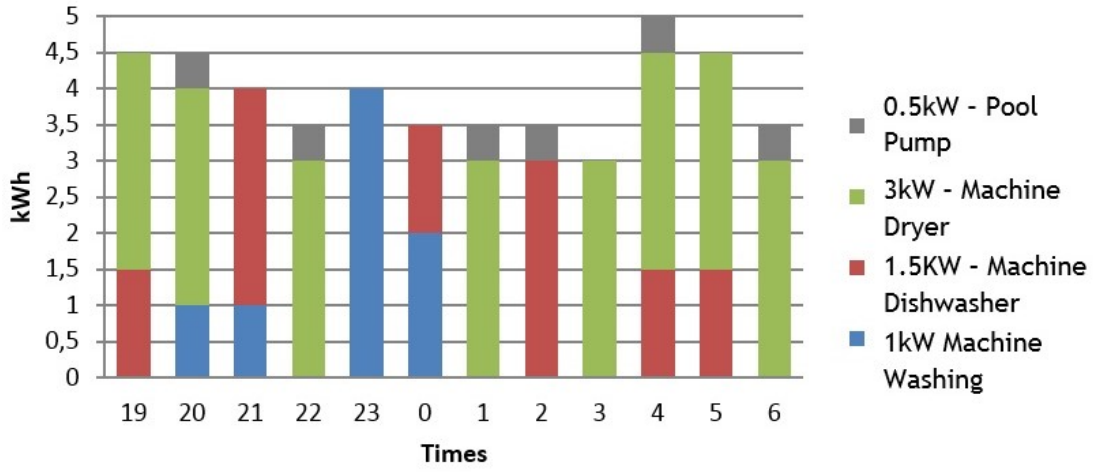


Figure 5.29. Scenario 2: Distribution of consumption 8 rooms with pool pump.

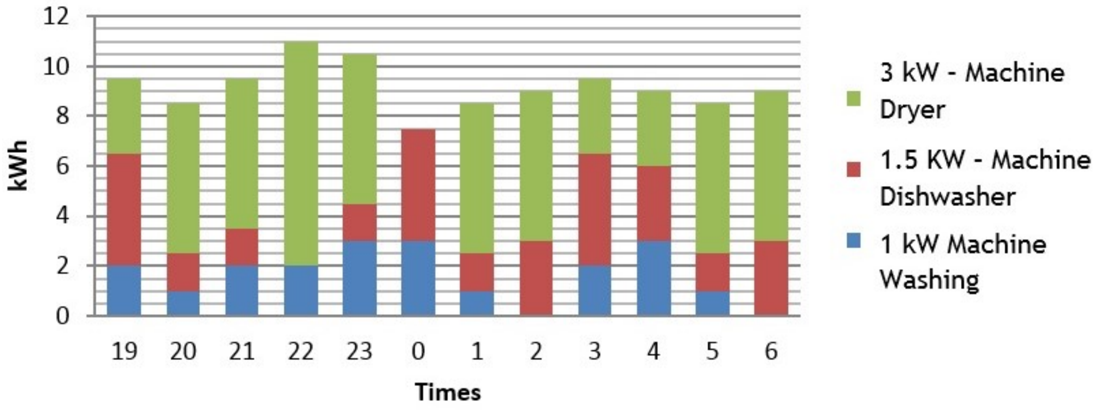


Figure 5.30. Scenario 3: Distribution of consumption 20 housing.

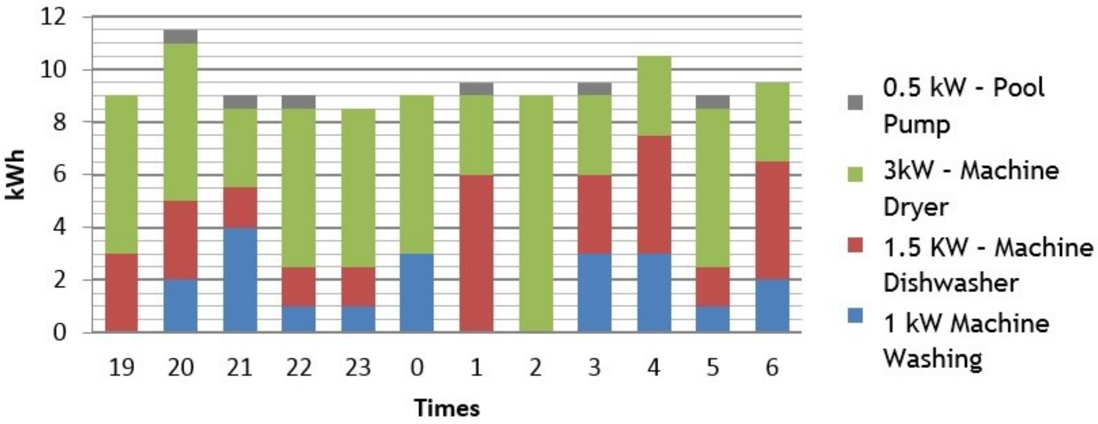


Figure 5.31. Scenario 4: Distribution of consumption 20 households with pool pump.

Chapter 6

Conclusions

In this chapter the main conclusions of the thesis are highlighted on the basis of answering the research questions that constituted the main motivation of this research. Then, several points to guide future research are proposed. Finally, the publications resulted from this researching work are listed.

6.1 Main Conclusions

The results presented in this thesis allowed to answer the questions raised in Section 1.3, describing the research questions to be addressed in order to mitigate the problems described in previous sections. Such findings are described below.

- What are the requirements of the Home Area Network (HAN) in the application areas that can benefit from this integration?

  A thorough analysis of wireless protocols for HAN was presented, comparing and discussing their advantages and downsides. In this study, short range wireless architectures have been considered as a key for a smart home enabled by wireless HAN. A key element for a smart home HAN to be a real possibility is to integrate a mixture of wired and wireless networks through an M2M gateway.

  The analysis has focused on two main families of standards: those built on IEEE PHY/MAC and on solutions that do not comply with IEEE standards. Their adequacy as regards major application area requirements in smart home solutions was investigated. No single wireless protocol analysed appears to satisfy the smart home functional areas' communication requirements as a whole. For energy management in smart homes, most of the low-power and low data protocols are adequate for this kind of function (such as MiWi, ZigBee, Wavenis, among others), with the exception of Insteon and EnOcean, which do not have enough security services. For medical and surveillance applications, Wi-Fi is better positioned.

Finally, UHD multimedia requirements will still be dependent on a wired infrastructure; however, the newer Wi-Fi protocol generations are on the right path to fulfill these requirements.

- How the evaluation of dynamic-pricing and peak power limiting-based Demand Response (DR) strategies is made with a bi-directional utilization possibility for Electric Vehicle (EV) and Energy Storage System (ESS)?

  A collaborative evaluation of dynamic-pricing and peak power limiting based DR strategies was studied. A distributed small-scale renewable energy generation system, V2H and V2G capabilities of an EV together with two-way energy trading of EV (using V2G option) and ESS was provided using a MILP framework based modeling of a HEM structure.

  Two-way energy exchange was allowed through net metering. The energy drawn from the grid has a real-time cost, while the energy sold back to the grid was considered to be paid a flat rate. This study made two basic assumptions. Firstly, the complete real-time pricing signal was known perfectly before the beginning of the off-line optimization horizon. Also, the user preferences and consumption behavior were assumed to be accurately known. Real data from a typical 4-member Portuguese family house and a PV plant were used. Several test cases were examined. The impacts of an extra DR strategy based on peak power limiting were also investigated. At the base case it was assumed that consumers were willing to charge their EV as soon as they arrive home and they own neither HEM system, nor ESS.

  Compared to this base case, which is also associated with the most expensive daily operation, the proposed strategy provided a more efficient operation by means of electricity cost reduction, reaching about 65%, which is significant. By adding more smart technologies, the operation that is coordinated by a HEM system offers a more economically efficient use of electricity. Indeed, smart technologies that will emerge in the future will provide more flexibility and economic possibilities for an end-user to participate into the power market, provided that the electricity market regulatory framework keeps up with the technological advances. Surely installation costs should also be considered in order to assess the actual benefits of such investments.

- The new developments of mono-phase power measuring systems can enable advanced measurements in the domestic sector?

  The power related readings were acquired and processed in real time and sent to a remote terminal unit that runs as a data logger and provides human-machine interface functionality. The communication is established through an RF link based on ZigBee protocol.

  The system had some advanced measurement capabilities. It can track the energy profile of conventional loads as well as non-linear loads such as those found on electronics operated appliances. The power meter's high bandwidth acquisition allowed reactive power and energy reactive readings with high harmonic distortion. In this sense, the voltage and current channels were prepared to measure electrical quantities with harmonic content up to 1kHz.

  High performance accurate measurements as required by modern standards for electricity meters could not be met since a low cost ADC solution that is part of general purpose microcontroller was used. This means that the accuracy obtained was limited by the internal ADC resource featuring 12-bit noise-free resolution. However, as a tool for monitoring energy consumption, the present performance can give a useful insight to the home user.

- What is the impact of MPC and other optimization technologies on energy savings of residential households?

  The results have shown that the MPC can improve the energy efficiency of the overall appliances, totalizing a reduction about 1.3%. Furthermore, to enhance savings on energy bills, an off-grid solar photovoltaic system was integrated into the home power system and its capacity utilization rate analysed according to the settings of the three appliances as a function of the control method. Concerning the integration, simulation results have shown that the solar capacity utilization ratio has an upper limit around 87.54% for TH operation, while with MPC operation is lower, at around 85.87%. Finally, by opting for an MPC method with local solar integration, a total reduction of 9.14% in the electricity bill was attained, which is significant. Hence, for a timeframe of 24 hours, the simulation results proved a reduction in the consumed energy with the MPC controller.

6.2 Guidelines for Future Contributions

Based on the research carried out in this work, and the results obtained, the following topics may become guidelines for future research work, helping to mitigate even more the problems described in previous sections.

These topics are:

- The proposed methodology can be easily adapted to larger formulations including shiftable appliances (washing machine and dishwasher) and other controllable appliances (HVAC) for extending smart household concept.
- The optimum operation of a neighborhood consisting of multiple smart households is also an extension of the proposed methodology, changing the objective function to be a minimization or maximization problem from the perspective of LSE of a multi-objective problem considering both the benefits of LSE and end-user household owner.
- The performance and accuracy of the measurements should be improved to be in accordance with modern standards for electricity meters. An enhanced and probably more expensive ADC solution should be designed.
- Disturbances in the system should be introduced in the systems for the MPC, so that they are more akin to reality, for example, the introduction of disturbances of opening and closing the refrigerator door, and the temperature variation of the water that enters the boiler.

6.3. Research Contributions Resulting from this Work

This section presents the various publications in peer-reviewed journals, book chapters and conference proceedings resulting from the research work carried out in this thesis.

6.3.1. Articles in Journals

[JP1] T.D.P. Mendes, R. Godina, E.M.G. Rodrigues, J.C.O. Matias, J.P.S. Catalão, "Smart home communication technologies and applications: wireless protocol assessment for home area networks resources", **Energies**, Vol. 8, No. 7, pp. 7279-7311, July 2015 **(Impact Factor of 2.072)**.
http://dx.doi.org/10.3390/en8077279

[JP2] O. Erdinc, N.G. Paterakis, T.D.P. Mendes, A.G. Bakirtzis, J.P.S. Catalão, "Smart household operation considering bi-directional EV and ESS utilization by real-time pricing-based DR", **IEEE Transactions on Smart Grid**, Vol. 6, No. 3, pp. 1281-1291, May 2015 **(Impact Factor of 4.252)**.
http://dx.doi.org/10.1109/TSG.2014.2352650

[JP3] T.D.P. Mendes, E.M.G. Rodrigues, R. Godina, J.P.S. Catalão, "Experimental results on a wireless wattmeter prototype for integration in home energy management systems", **Energy (Elsevier)**, **(Impact Factor of 4.844)** (submitted).

6.3.2. Book Chapters

[BC1] E.M.G. Rodrigues, T. Caramelo, T.D.P. Mendes, R. Godina, J.P.S. Catalão, "Experimental wireless wattmeter for home energy management systems", in: Technological Innovation for Cloud-based Engineering Systems, Eds. L.M. Camarinha-Matos, T.A. Baldissera, G. Di Orio, F. Marques, DoCEIS 2015, IFIP AICT 450, **SPRINGER**, Heidelberg, Germany, pp. 327-336, April 2015.
http://dx.doi.org/10.1007/978-3-319-16766-4_35

[BC2] E.M.G. Rodrigues, R. Godina, T.D.P. Mendes, J.C.O. Matias, J.P.S. Catalão, "Influence of large renewable energy integration on insular grid code compliance", in: Technological Innovation for Cloud-based Engineering Systems, Eds. L.M. Camarinha-Matos, T.A. Baldissera, G. Di Orio, F. Marques, DoCEIS 2015, IFIP AICT 450, **SPRINGER**, Heidelberg, Germany, pp. 296-308, April 2015.
http://dx.doi.org/10.1007/978-3-319-16766-4_32

6.3.3. Papers in Conference Proceedings

[PC1] N. Neyestani, M.Y. Damavandi, T.D.P. Mendes, J.P.S. Catalão, G. Chicco, "Effect of plug-in electric vehicles traffic behavior on multi-energy demand's dependency", in: Proceedings of the **IEEE EnergyCon 2016** Conference, Leuven, Belgium, April 4-8, 2016 (accepted).

[PC2] D. Oliveira, E.M.G. Rodrigues, R. Godina, T.D.P. Mendes, J.P.S. Catalão, E. Pouresmaeil, "MPC weights tunning role on the energy optimization in residential appliances", in: Proceedings of the 25th Australasian Universities Power Engineering Conference – **AUPEC 2015** (technically co-sponsored by **IEEE**), Wollongong, Australia, 27-30 September, 2015.
http://dx.doi.org/10.1109/AUPEC.2015.7324869

[PC3] D. Oliveira, E.M.G. Rodrigues, R. Godina, T.D.P. Mendes, J.P.S. Catalão, E. Pouresmaeil, "Enhancing home appliances energy optimization with solar power integration", in: Proceedings of the **IEEE** Region 8 International Conference on Computer as a Tool – **EUROCON 2015**, Salamanca, Spain, 8-11 September, 2015.
http://dx.doi.org/10.1109/EUROCON.2015.7313798

[PC4] D. Oliveira, E.M.G. Rodrigues, T.D.P. Mendes, J.P.S. Catalão, E. Pouresmaeil, "Model predictive control technique for energy optimization in residential appliances", in: Proceedings of the **IEEE** International Conference on Smart Energy Grid Engineering – **SEGE'15**, Oshawa, Canada, August 17-19, 2015.
http://dx.doi.org/10.1109/SEGE.2015.7324578

[PC5] O. Erdinc, N.G. Paterakis, T.D.P. Mendes, A.G. Bakirtzis, J.P.S. Catalão, "Smart household operation considering bi-directional EV and ESS utilization by real-time pricing based DR", in: Proceedings of the **IEEE Power Tech 2015** Conference, Eindhoven, Netherlands, 29 June - 2 July, 2015.

[PC6] T.D.P. Mendes, R. Godina, E.M.G. Rodrigues, J.C.O. Matias, J.P.S. Catalão, "Smart and energy-efficient home implementation: wireless communication technologies role", in: Proceedings of the 5th International Conference on Power Engineering, Energy and Electrical Drives – **PowerEng 2015** (technically co-sponsored by **IEEE**), Riga, Latvia, May 11-13, 2015.
http://dx.doi.org/10.1109/PowerEng.2015.7266346

[PC7] O. Erdinc, T.D.P. Mendes, J.P.S. Catalão, "Impact of electric vehicle V2G operation and demand response strategies for smart households", in: Proceedings of the 2014 **IEEE** PES Transmission & Distribution Conference & Exposition – **T&D 2014**, Chicago, Illinois, USA, 14-17 April, 2014.
http://dx.doi.org/10.1109/TDC.2014.6863277

[PC8] T.D.P. Mendes, G.J. Osório, E.M.G. Rodrigues, J.P.S. Catalão, "Energy management in smart homes using an experimental setup with wireless technologies", in: Proceedings of the International Conference on Engineering UBI 2013 — **ICEUBI 2013**, Covilhã, Portugal, November 27-29, 2013.

6.3.4. Technical Report

[TR1] G. Chicco, V. Cocina, P. Di Leo, A. Russo, F. Spertino, J. Contreras, D.H. Alamo, T.D.P. Mendes, E.M.G. Rodrigues, A.W. Bizuayehu, J.P.S. Catalão, P. Medina Núñez, E. Skoufa, "Report on requirements, applications, and definition of advanced EES management methods for insular networks", **Technical Report D3.1**, Theme [Energy.2012.7.1.1] Integration of Variable Distributed Resources in Distribution Networks, **Project FP7-EU SiNGULAR**, February 2015.

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